Study of a 5 GHz CMOS RF Transmitter Integrated on Batteryless Smart Contact Lens for Covid-19 Monitoring

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THESIS

Degree of Master of Science in Electrical and Computer Engineering in the Graduate College of the Politecnico di Torino, 2021

Torino, Italy

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Per tutte le esperienze, le nozioni e le persone che ho potuto imparare, conoscere e vivere negli anni che hanno portato alla conclusione dei mie studi, ringrazio, con immensa felicitá, La Mia Famiglia.

For all the experiences, the notion and the people that I have learned, known and lived in the years that have brought to the end of my studies, thank you, with immense happiness, to My Family.

ACKNOWLEDGMENTS

I would like to gratefully acknowledge various people who have been journeyed with me in my university carrier. First of all, I would like to thank my advisor, Professor Danilo Erricolo, my co-advisor, Professor Giuseppe Vecchi, for their ideas, feedback, time and encouragement. Thank you also to all the committee members.

I am very grateful to the research group I work with. Thank you to Anastasiia who helps me in the literature and in the sensor part. Thank you to Alex who helps me in the use of the software. Thank you Yangqing who helps me in the general understanding of the research.

Finally, I want to express my gratitude to my family and friends, who have helped and encouraged me throughout my studies.

AB

CONTRIBUTIONS OF AUTHORS

In the first chapter of this thesis we describe already existing researches about the use of smart contact lenses used for the health monitoring. It was important to do this research before starting with the design of our system to correctly and fully understand the project that we want to realize. Thanks to the studies of J. Kim et al. (1) we have an overall idea of already existing wearable technologies and in which kind of direction they were grow during the history.

After this steps we moved to the understanding of smart contact lenses already designed by others starting with the work of H. Yao, Y. Liao et al. (2) in which we analyzed a pretty old smart contact lens and then thanks to the work of J. Park, J. Kim et al. (3) we were able to detect the advantages of more recent research respect to the old one. This comparison step was really important to fully understand all the choices that were taken during the history of this devices, the smart contact lens.

Then, after we have understood the advance make in the design of the smart contact lenses we have decided to analyze the different applications where they are already used to understand if our application can be realized. Analyzing the work of J. Kim, M. Kim et al. (4) and J. Park, J. Kim et al. (3) we understand what are the circuits necessary for this kind of application and how to share the information contained in the smart contact lens with the outside world. Secondly, we analyze the use of smart contact lenses for the glaucoma diagnosis with the works of Agaoglu et al. (5) and G. Chen et al. (6). Third, we also found researches about monitoring cortisol concentrations with the paper of M. Ku, J. Kim et al. (7). Finally, the last used that we found in literature was the drug delivery studied by Kim et al. (8). This part of our research help us to understand how smart contact lens are used today and so to understand if our idea of future application can be effectively realized. Thank to this study we were able to explain in the Technological Developments section what are the most important improvement in technology that can be used in our research and we also explain what are our choices and why.

In the second section we analyzed how to realize the design of the smart contact lens used in this project. The main purpose of this thesis is about the transmitter part used for our smart contact lens but understanding the overall circuit helps to understand all the specifications that are required by the transmitter part. Thus, we analyzed the different kind of circuits needed to realize a working smart contact lens.

A. Rozhkova work was concentrated on the GFET aptasensor part that take similar ideas of the M. Stroscio studies (9), (10) and (11). Moreover, the use of graphene for the chemical analysis in fluids has already been studied in other researches such as (12), (13) and (14) that we have a briefly analyzed in this section.

After this, the rectifier part was studied by A. Stutts while for the transmitter part we started to underline in this section some important designed already used in literature (15), (16), (17), (18), (19). In this section we presents also the antenna decided to be used in the smart contact lens project that was studied by Professor Danilo Erricolo.

After these two sections about the literature and the overall circuit, the smart contact lens, section three starts to explain more in detail the focus of this thesis, the transmitter design. This sections starts with an analysis of already used transmitter in wearable devices with the study of Zhao B. et al. (20), the study of Jeon C. et al. (18) and the one of Merenda M. et al (19). Then it presents the transmitter designed used in our work with a focus in all the required circuits. The first circuit explained is the LC-cross-coupled oscillator and its parameters that we have decided to use in functions of all the specifications that we have to satisfy given by the analysis made in the two section above. Its design was also compared with the design of the papers presented before (20),(18) and (19). The second circuit presented is a power amplifier and here we explain is importance in the designed of the transmitter part.

The four section is about the LT-Spice simulation design and result of the circuit explain in the section above. Thanks to this section we were able to demonstrate the expected results of the LT-Spice in function of all the study and decision that we have made in the sections above. Here we explain the topology of CMOS used, the 0.35 µm CMOS, the varactor technology used instead of capacitors studying the structure used by Bunch et al. in their work (21).

In chapter five we have proposed how to do the transmitter fabrication in function of our environment, the smart contact lens. We analyzed a work in which was fabricated a transmitter for a smart contact lens the one of Joen C. et al. (18) and other work about flexible technologies Vilouras A. et al. (22). The understanding of these two papers helps us to find the propose idea for the fabrication of a flexible transmitter.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

FIGURE **PAGE**

LIST OF FIGURES (Continued)

SUMMARY

Our work is focused on building a 5 GHz transmitter for a wireless and battery-free smart contact lens.

In the first section we analyzed smart contact lenses that are already used in literature for health monitoring. We describe their basic structure with a focus and comparison between two research groups, H. Yao et al. (2) and J. Park et al. (3) by analyzing the two different approaches. Next, we investigated smart contact lens applications for health monitoring as: diabetes diagnosis, glaucoma diagnosis, cortisol concentration monitoring and drug delivery. Then, we present our idea to a future smart contact lens application, the detection of SARS-COV-2. Finally, we describe the technological developments carried out over years of research to improve the fit and comfort of wearable devices.

In section two we present the complete design of our smart contact lens composed of an antenna, a power supply circuit, a transmitter and a GFET sensor for Covid-19. We describe the antenna used which is transparent, flexible and small in size to integrate on the smart contact lens. Next, we analyze the sensor circuit made with graphene field effect transistors that is starting to be used in the field of internet of thing technologies instead of silicon. This type of technology has in fact very good high frequency performances and also has chemical characteristics that make them perfect for the analysis of human fluid. For the sensor part we decided to also use aptamers to reduce the number of false detections.

The third section is focused on the transmitter part and its design is the purpose of this work. First, we describe transmitter circuits already used for wearable devices and we underline the specification and the most important features that our transmitter must have to by integrated on the smart contact lens. Next, we explain the circuits used for it realization: a cross-coupled LC oscillator, a power amplifier and current mirror. The cross-coupled LC oscillator was designed to convert the low frequency input signal into a high frequency output signal capable of being transmitted by the small loop antenna.

In section four we present the design and simulation result of the transmitter circuit designed with LT-Spice. We first describe the realization of each component separately and then we analyze the output result of the complete transmitter. We decided to use 0.35 μm CMOS technology for it realization and we also describe the library used with LT-Spice to use this specific technology.

Finally, in section five we describe how perform the fabrication of the transmitter circuit. We start from the analysis of works already present in literature that use transmitter in wearable devices. After this study we describe how to obtain a flexible circuit with a thickness of 100 μm which can be easily integrated on the smart contact lens.

CHAPTER 1

INTRODUCTION

1.1 Wearable Technologies for Healthcare Monitoring

Recent advances in wearable technology open the door to new healthcare monitoring.

The idea to provide continuous, real-time physiological information is becoming more and more real thanks to the development of wearable electronics combined with wireless communications. Such real-time monitoring can provide patients health information, keep chronic diseases under control and send a message of an abnormal or unexpected situation alert to the user or to doctors.

An import advantage of wearable technologies is that they can perform dynamic, noninvasive measurement of biochemical markers in human fluids, such as sweat, tears, saliva and interstitial fluid. In this way, wearable biosensors can take the place of painful and invasive technologies for the healthcare monitoring that use blood sampling procedures. Furthermore, they can be worn continuously without changing the wearer's daily routine.

Recent developments focusing on electrochemical and optical biosensors, along with advances in non-invasive monitoring of biomarkers such as metabolites, bacteria and hormones are at the base of wearable technologies. For example, to enhance their wearability and practicality a merge of multiplexed bio-sensing, microfluidic sampling and transport systems have been integrated, miniaturized and combined with flexible materials to provide the necessary flexibility and elasticity (1).

A precised and valid real-time detection of physiological data, performed using wearable biosensor technologies, would have a great and good influence on our daily lives.

The path of biosensor development for wearables is visible in Figure 1.

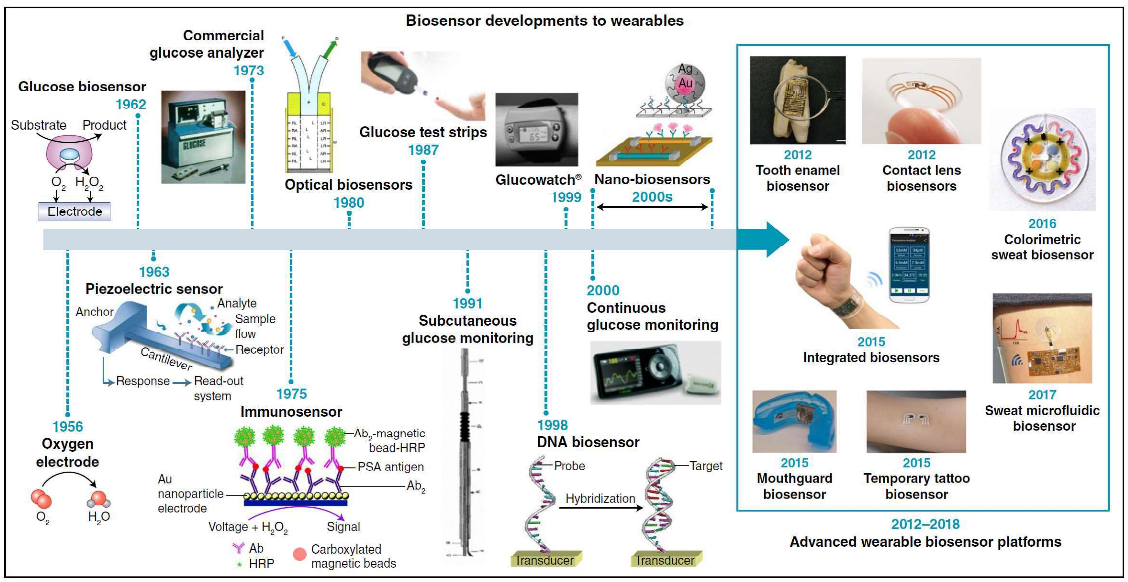

Figure 1: Path of biosensor development for wearables. This image is taken from the work of J. Kim et al. (1) in their Figure 1 b, © Springer Nature America, Inc. 2019.

1.2 Smart Contact Lens State of Art

Given this introduction on wearable technologies for the healthcare monitoring we want to focused on a specific one, a smart contact lens. The accuracy and endurance of a smart contact lens have been examined considerably, and important progress have been realized to reduce irritability of eyes and to increase the user's wearability (3).

Here we present two different research papers that fabricated two different contact lenses. The first is the work of H. Yao, Y. Liao et al. (2) and is important to mention because it explains how to make the basic design of a working smart contact lens, giving an idea of both the overall system and the individual components. However, this study was performed in 2012 and a lot of benefits have been performed in the field of wearable technologies. We emphasize how the fabrication of a smart contact lens has changed between years by presenting the research of J. Park, J. Kim et al. (3). Through this study, we understood how to modify the simplest idea of smart contact lens explained by H. Yao, Y. Liao et al. (2) and we were able to make some decisions to design a small transmitter.

1.2.1 A contact lens with integrated telecommunication circuit and sensors of H. Yao, Y. Liao et al.

Initially, H. Yao, Y. Liao et al. (2) realized a contact lens with an integrated circuit that is flat and rigid so, it is no ideal for a contact lens because it can damage the cornea, but anyway a good start for this kind of technology.

In their study they present an integrated functional contact lens used to monitor tear glucose levels wirelessly. It is form by a glucose sensor, metal connections, a circuit used for reading the sensor, antenna and telecommunication component. Thanks to absence of wires it start to be more suitable for wearable purpose. In their study they reported the architecture and fabrication of a low power consumption sensor (3 μW) and a telecommunication component to provide power without connections and to transmit sensor data.

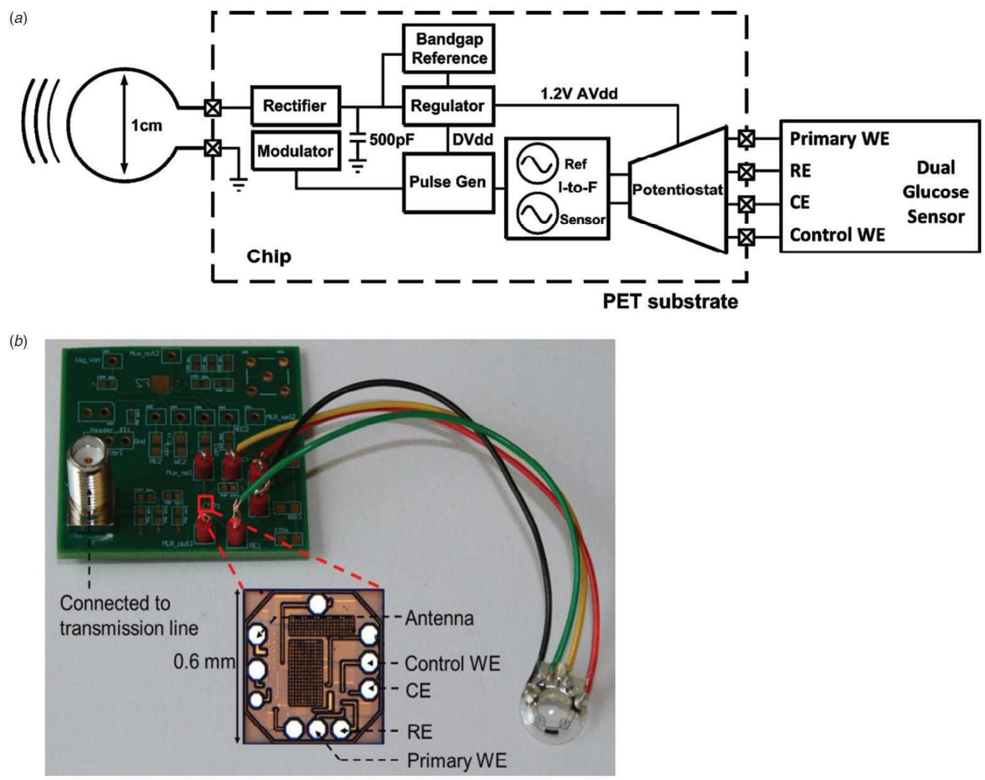

Figure 2: (a) Communication circuit design. (b) Connection of the glucose sensor and the communication circuit realized on a PCB. This image is taken from the work of H. Yao et al. (2) in their Figure 3, © 2012 IOP Publishing Ltd.

The chip manifactured by H. Yao, Y. Liao et al. is composed of a rectifier, a regulator, a bandgap reference circuit, a modulator, a pulse generator and an oscillator and a scheme is reported on Figure 2 a. This chip is connected to the antenna and thanks to it the received radio frequency wave power is transformed into DC power. Hence, this power is usable for the sensor without the need for wires.

The readout system is fully integrated in a small chip, Figure 2 b (0.6 mm $\times$ 0.6 mm, 200 μm thickness), its thickness is the minumun one that allows it wearability, for this reason is important underline progresses in the material used for wearable electronics. In fact, this study was performed across 2010 and 2012 and great advantages in new kind of material are studied today to realize a more comfortable and wearable contact lens.

For what concerned the sensor, various methods can be used to realize a sensor sensible to glucose. The sensor realized in this research is a differential sensor with large connection pads that are incorporating in the contact lens to perform the base characterization of the sensor performance. The sensor consists of two equivalent sensors, one is the primary sensor and the other is used for the control. They are designed with a working electrode and a counter electrode. The counter electrodes of these two sensors are attached together and the overall sensor has one common reference electrode, as shown in Figure 3 (2).

Another important component used in the smart contact lens of H. Yao, Y. Liao et al. (2) is the antenna. The primary difficulty for its design is to obtain enough efficiency even with small dimension systems. The size of the antenna highly affects its efficiency and decreases sharply if the antenna is tinier than the electromagnetic wavelength. So to solve this problem

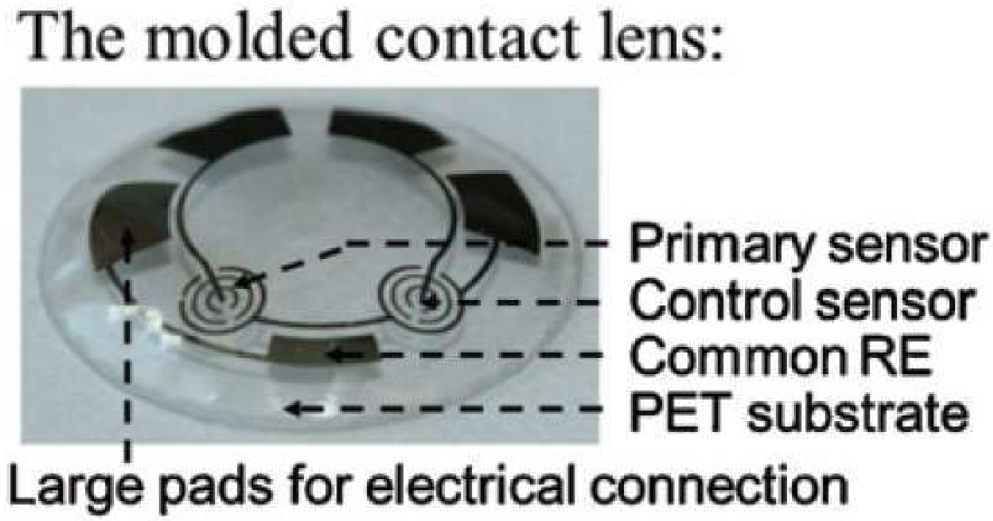

Figure 3: Dual sensor in the modeled contact lens. This image is taken from the work of H. Yao et al. (2) in their Figure 1 b, © 2012 IOP Publishing Ltd.

and improve the efficiency with a small antenna it has to work at high frequency. For this reason, they chose a frequency band of 2.4 GHz. To use this kind of antenna in a contact lens is important that it does not impede vision, it is not made with transparent material so H. Yao, Y. Liao et al. (2) decided to realize a loop antenna that can be located on the boundaries of the contact lens.

1.2.2 Soft, smart contact lenses with integration of wireless circuits, glucose sensors, and displays of J. Park, J. Kim et al.

An other group of research in 2018 (3) realized a new kind of smart contact lens that is more comfortable for the user thanks to all the advantages in materials that they utilize for the substrate, sensors and antenna, visible in Figure 4. Soft and smart contact lenses have been studied a lot to improve their wearability and stability and relevant improvements have been realized to reduce irritation of the eye and to increase the user's comfort.

J. Park, J. Kim et al. (3) point out some significant issues that need to be addressed before practical uses of smart contact lenses can be realized. First, the use of non transparent electronic materials for chips and interconnects can obstacle users' vision. Second, components of the electronic device that are integrated on flat and plastic substrates can irritate users' eyes and eyelids because they create foreign objects when transformed into the curved shape for lenses, they result in buckled deformations. Furthermore, the fragile and flat materials used for the integrated electronic system, like chip surface and rigid interconnects, could hurt the user's eye. Finally, another issue is given by the the requirement of voluminous and costly equipment for signal measurements, which restricts the use of smart contact lens out of laboratories and so it limits users' external activities. A lot of these problems are visible in the previous study of H. Yao, Y. Liao et al. (2).

To achieve these goals, for the design of soft contact lens, J. Park, J. Kim et al. (3) decided to use transparent and flexible hybrid structures. They are divided in two region, one is a mechanically reinforced island to locate discrete electronic devices (for example rectifying circuits and display pixels) and the other one is an elastic region to locate a stretchable, transparent antenna and interconnect electrodes. However, a disadvantage in the use of hybrid substrates is that they can drastically reduce the optical properties of the final films, obtaining low transparency and high haze due to the disparity in the refractive indices of heterogeneous components. Fortunately, this problem can be resolved using heterogeneous materials with negligible deviations in the refractive indices that can provide a transparency (93% in the visible spectrum) and a low haze (1.6% in the visible spectrum) giving a good and clear view at the wearer.

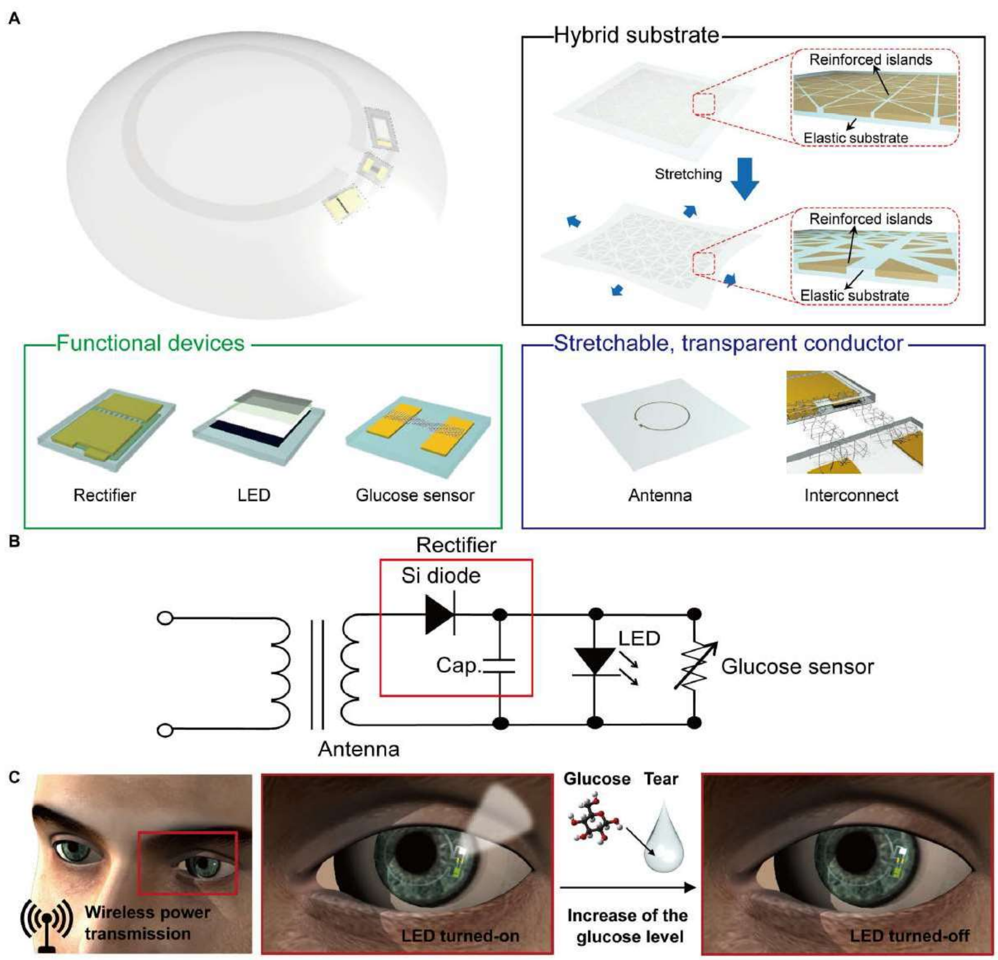

Figure 4: Design of the smart contact lens. This image is taken from the work of J. Park et al. (3) in their Figure 1, Copyright © 2018 (CC BY-NC).

J. Park, J. Kim et al. (3) used electrodes for passive components, such as antenna and interconnects, which occupy relatively large areas of the final IC, and therefore to not obscure the view of the wearer they must have high transparency and flexibility. Thus, to create transparent and stretchable electrodes one-dimensional, long metal nanofibers were electrospun as continuous networks. Furthermore, their flexibility can prevent mechanical deformation of devices on the contact lens and so it can irritate less the eye or eyelid than the presence of foreign objects.

For what concerned the sensor, J. Park, J. Kim et al. (3) used a glucose sensor where the glucose level is shown by a LED pixel. In this way the glucose can be monitored because its change is simultaneous with the information given by the LED. However, the use of a LED is a limitation in the monitoring of the disease because it only shows the presence of abnormal amount of glucose without giving precise information about the correct value of glucose.

Thanks to a pyrene linker through the p-p stacking interaction the sensor is able to immobilize the glucose oxidase on the graphene surface. However, the repeated forming of H_2O_2 can corrupt the enzymatic activity of GOD, overcast the sensitivity of the glucose sensor. So, to eliminate H_2O_2 instantaneously, J. Park, J. Kim et al. (3) decided to use catalase (CAT), which can decompose H_2O_2 into H_2O and O_2. Furthermore, the use of catalase improved the sensitivity of the sensor by increasing the enzymatic activity of glucose oxidase.

1.3 Smart Contact Lens Applications

The use of wearable devices has changed fast in recent years, first being studied by researchers to monitor physical activity and now they are focused on healthcare applications, such as diabetes supervision or remote control of older people (1). To realize these intentions, the scientists studied and fabricated wearable biosensors, described as sensing devices that merge a biological detection element into the sensor's (such as antibody, enzyme, organelle or cell receptor).

For example, a contact lens can collect user's tears without invasive devices with normal secretion and blink. It can be used to evaluate various bio-markers that can also be found in the blood, such as glucose, cholesterol, sodium ions, and potassium ions. Therefore, a great advantage of sensor-equipped smart contact lenses is that they can provide noninvasive methods to continuously detect metabolites in tears (3).

A typical biosensor contains two basic functional units: a 'bioreceptor' (such as enzyme, antibody or DNA) which recognizes the pointed analyte and a physico-chemical transducer (such as optical, electrochemical or mechanical) which converts the bio-recognition into a signal that can be used to transmit information (1).

1.3.1 Diabetes Diagnosis

To overcome conventional invasive diagnostic tests such as, finger pricking for blood sampling Figure 5 (a), several researchers such as Park et al. (3) studied a noninvasive detection of glucose levels for the diagnosis of diabetes among various bio-markers Figure 5 (b). They (3) considered the correlation between tear glucose level and blood glucose level, a contact lens-mounted glucose sensor can provide the noninvasive monitoring of the user's glucose levels from tear fluids.

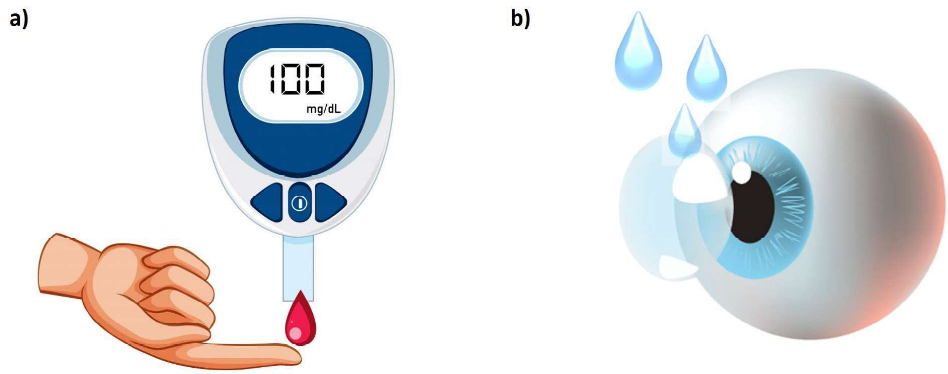

Figure 5: (a) finger pricking for blood sampling (https://www.vecteezy.com/vector-art/359833-medical-blood-glucose-measurement, © 2021 Eezy Inc. All rights reserved). (b) contact lens-mounted glucose sensor which monitors of the user's glucose levels from tear fluids.

Other researcher such as J. Kim, M. Kim et al. (4) analyzed different types of materials needed for biosensors operating on soft contact lenses. They require transparency, flexibility and reliability to withstand repeated bending and stretching. The materials that meet these requirements are: graphene, carbon nanotubes (CNTs), metal nanowires (mNWs), metal mesh structures, conductive polymers and their hybrid structures. In particular, they reported that the graphene-silver nanowire (AgNW) hybrid structure has electrical, transparent and mechanical properties, it is also suitable and stretchable, therefore perfect to realize transparent electrodes for the smart contact lens. Hence, they (4) make a FET-based glucose sensor which is composed of the graphene channel and hybrid S/D which can acts as a painless and cost-effective substitute to the current approach.

However, graphene has also disadvantages, J. Kim, M. Kim et al. (4) said its grain edges can reduce the success of the seal, particularly if the lenses are worn for a lot of time. Anyway, two-layer passivation can grantee acceptable sensor security against ocular fluids for the daily disposable contact lens. Additionally, contact-lens device must be worn so it should also have a high-oxygen and water permeability, instead of lens shaped polyethylene terephthalate or PDMS substrates. The substraited chosen by J. Kim, M. Kim et al. (4) was Parylene because it has intraocular biocompatibility and also mechanical advantages like strength and elasticity that different plastic materials has not. Additionally, it has big transparency and pinhole-free compliant deposition so it acts as a very good substrate for the system on the contact lenses.

1.3.2 Glaucoma Diagnosis

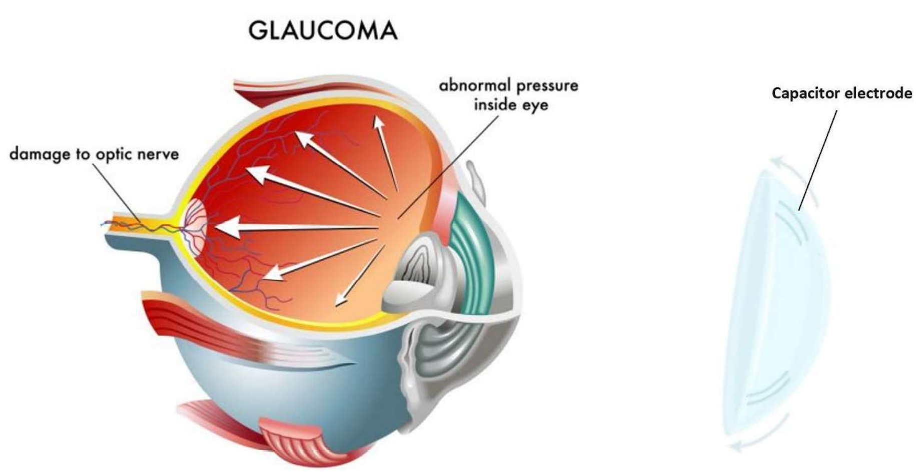

Figure 6: Schematic of a smart contact lens with a low force capacitive sensor used to continuously monitor the intraocular pressure. (https://www.klipartz.com/en/sticker-png-htqer)

Glaucoma is a neurodegenerative disease that causes irreversible and progressive loss of vision. High intraocular pressure (IOP) is the main and only modifiable risk factor for glaucoma and has diurnal fluctuations. Unfortunately, these fluctuations can skew medical analysis of the disease progression. Therefore, the need of continuous analysis is required to perform accurate IOP measurements for effective management of glaucoma. This is accomplished by the smart contact lens realized by Agaoglu et al. (5).

In an other work, carried out by G. Chen et al. (6), a smart contact lens with a low force capacitive sensor is used to continuously monitor the IOP, Figure 6. They used a new design with a capacitive sensor which is perfect for low force applications like in this one. It differs from previous research that relying on strain sensing elements to convert the force into characteristic signal. To simplify wireless signal transmission, LC resonant circuit is composed of a curvature sensing capacitor which is coupled with a fixed inductance inductive coil. The resonance frequency of the LC circuit and the capacitance would change as a function of changes in the curvature of the cornea. In addition, the resonance frequency can be read wirelessly by a receiver installed on a glass frame worn by the user.

1.3.3 Monitoring Cortisol Concentrations

Smart contact lens can also be apply to monitor cortisol concentrations. Despite conventional approaches that require bulky external equipment, the use of contact lenses do not limits their use as mobile healthcare systems. Therefore, their development means a noninvasive and wearable sensors that can accurately monitor cortisol concentration, so it is an improvement for a smart healthcare solution.

Some researcher such as M. Ku, J. Kim et al. (7) described in their research a real-time detection of cortisol concentration in human tears with the use of a smartphone. Their smart contact lens (Figure 7) does not obstruct the wearer's view and it uses stretchable interconnects to connect their sensor, antenna, capacitors, resistors, and integrated circuit chips.

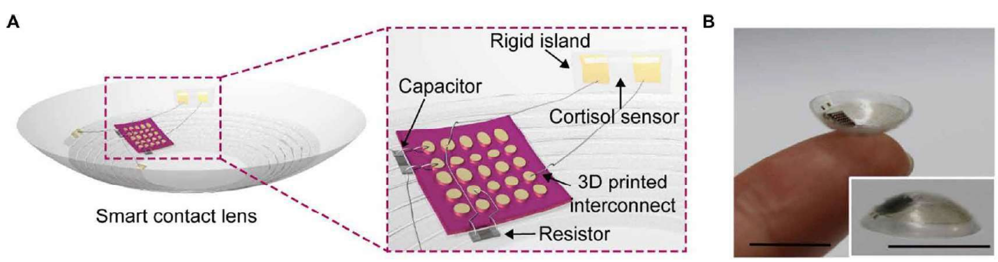

Figure 7: Diagram of the packaged smart contact lens with a rigid island for the sensor and stretchable interconnects. This image is taken from the work of M. Ku et al. (7) in their Figure 4, Copyright © 2020 (CC BY-NC).

The sensor is realized with a GFET capable of measuring cortisol concentration with a threshold of 10 pg/ml, which can guarantee the detection of cortisol in tears fluid.

The contact lens system, realized by M. Ku, J. Kim et al. (7), uses NFC function. Their wireless circuit is based on the passive communication mode of NFC which has no battery and the user's external mobile device applies a magnetic field to the antenna inside the smart contact lens to initiate communication. The antenna is an LC circuit in which the inductor behaves like a coil that induces current from the magnetic field. Hence, the resistance of the sensor is read by the near field chip and it transmits the data from the sensor wirelessly to smartphones. The ability to interact with cell phones is a great benefit of this research to help people monitor their health in a non-invasive and extremely simple way. Using smartphones to see cortisol concentration is easier than using other bulky devices that are difficult for normal people to use.

1.3.4 Drug Delivery

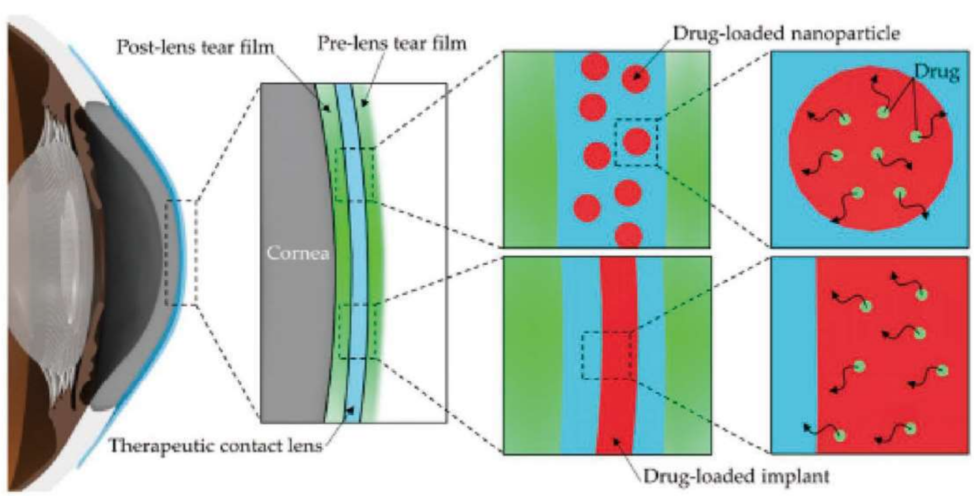

Figure 8: Schematic of drug release onto the ocular surface from drug-eluting therapeutic contact lens. This image is taken from the work of M. Ku et al. (8) in their Figure 7 a, © 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

Smart contact lenses can also be used to insert drugs into eyes by the method of inserting drugs directly in the eye. However, this methodology has the disadvantage that drugs can be cleaned speedily by the ocular fluids, so a lot of it does not stay in the eye. To solve this problem, Kim et al. (8) reported a methodology of constantly administering drugs into eyes by carrying drugs into the smart contact lens, as shown in Figure 8. A lot of drug delivery contact lenses have drug-loaded molecules integrated on them, and the particles are usually composed of microparticles, nanoparticles, liposomes, microemulsions, and micelles. However, a disadvantage of these particles can be their size because when they are large, they affect the optical transmittance of the contact lens. Thus, one way to overcome this problem is to mix the monomers of the lens with the drug-loaded particles prior to the manufacture of the lens.

In their study Kim et al. also presented the work of Jung et al. (8). They formed nanoparticles that can treat glaucoma by reacting propoxylated glyceryl triacrylate and timolol maleate. Next, the contact lens was molded by mixing the drug with the monomer of the lens material.

The possibility of loading drugs into contact lenses for therapeutic purpose is studied by many researchers, but a lot of researches have the disadvantage that the drug is delivered in bursts instantaneously when the contact lens is worn. Hence, they point out that controlling the drug release rate is a major challenge. Furthermore, the wearability of the smart contact lens is to take into consideration and the surface roughness of the lens given by this technology can irritate the eye. However, Kim et al. (8) explain how to expose the particles to the surface of the lens only after it has been manufactured by combining the particles with the monomer component of contact lenses.

1.3.5 Future Application: detection of SARS-COV-2

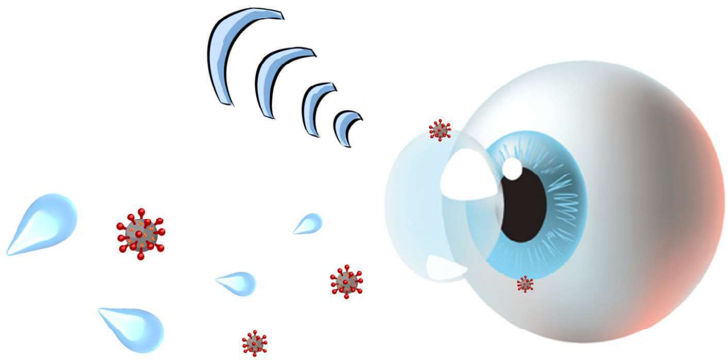

Figure 9: Schematic of a smart contact lens used for the covid-19 detection.

We have seen several smart contact lens applications that have already been studied by different research groups. The continuous monitoring of this type of technology offers many advantages in health monitoring by helping the patient to always be under control. Thanks to all the discoveries made in the field of wearable technology, smart contact lenses can be improved to become less invasive and more comfortable than those that already exist now. A new type of application that our research group wants to study is the detection of SARS-COV-2 with tear analysis, Figure 9.

Unfortunately, our historical period is characterized by the presence of the coronavirus which drastically changes our lifestyle. The rapid spread of the disease has created overcrowding in hospitals, a large number of infections and deaths around the world.

There are already different types of tests to check for the presence of the virus inside the human body but they are invasive and need to be performed in hospitals or specific medical centers. For such an ineffective disease it is important to find a new detection method that is faster and easier than conventional methods. In our research we want to make a smart contact lens that can detect the virus inside the tears. If the patient wears the lens before becoming positive for the virus, the lens is able to detect the time of infection before the patient starts having symptoms. For this reason this type of technology can help a lot in the fight against covid-19 because it can help people know if they have the disease and thus remain isolated and avoid more infections.

1.4 Technological Developments

Integrated circuit research on lenses is proposed at the beginning of Smart Contact Lens technology, such as the study by H. Yao, Y. Liao et al. (2). However, the idea of putting an integrated circuit on a contact lens is not a good idea. In fact, it is flat and stiff, so it can damage the cornea. the topography of the cornea can be damaged and undergo changes due to the presence of electronic systems placed on the surface of the contact lens which can cause its mechanical mismatch. Another important issue is to realize a circuit that does not limit the visibility of the eye and therefore to study different kind of material that are transparent. The use of metal components and sensors placed on contact lenses, can cause the problem of opacity that limits the patient's field of vision so it was necessary to go and study new types of materials that could solve this problem. As demonstrated by Kim J. et al (4) it is possible to make transparent electrical components that include graphene-silvernanowires. Third, the contact lens is placed inside an eye so that the environment is humid and the humidity is not so good for electrical devices, this is another aspect that has to be considered. Recently, Jiang et al. (23) recommended the use of microfluidics to improve air permeability in contact lens sensors. Finally, we have that the circuit has to work for a long time such as for a full day or more because it must be able to analyze the tears at all times and communicate anomalies.

M. Ku et al. (7) also studied the thermal stability of the sensors that they use in their smart contact lens. The working environment of the contact lens is in a temperature range between 22 ° C (room temperature) and 36.5 ° C (body temperature) so the cortisol sensors were tested at these two temperatures for 192 hours going to vary the concentrations of cortisol. After this test there was no degradation of the sensitivity of the sensors, which indicated that, for at least 192 hours, the enzymes remained active.

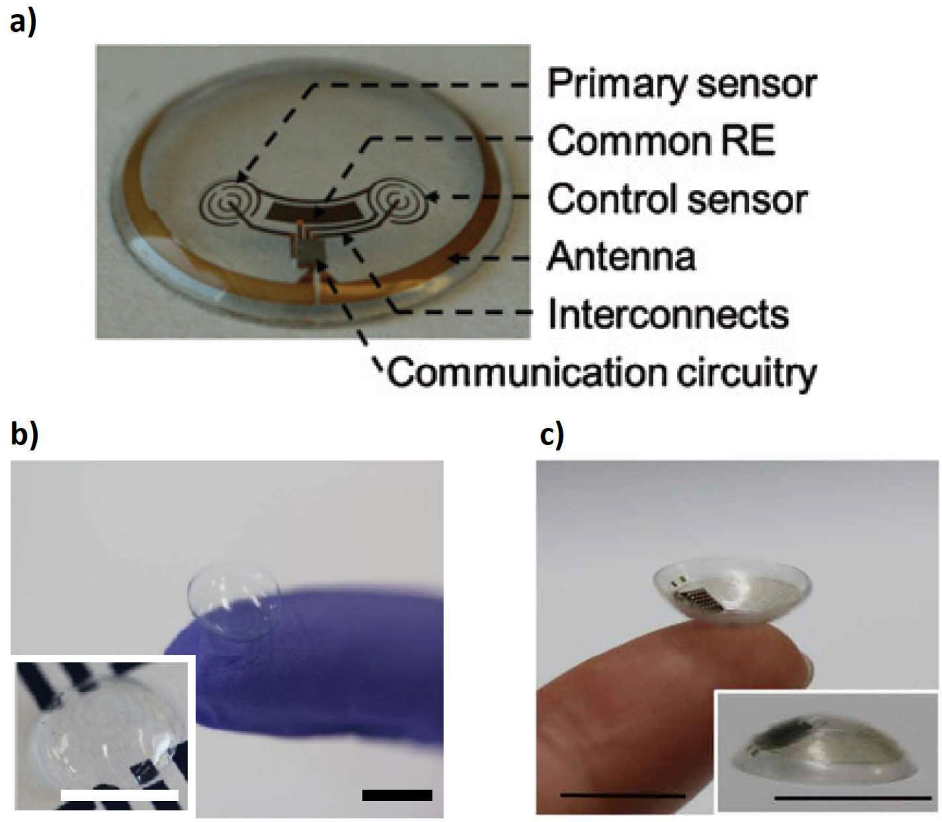

Figure 10: (a) Smart Contact Lens of H. Yao et al. (2) from their Figure 4 h, © 2012 IOP Publishing Ltd (b) Smart Contact Lens of J. Kim et al. (4) from their Figure 1 b, © The Author(s) 2017 (c) Smart Contact Lens of M. Ku et al. (7) from their Figure 4 b, Copyright © 2020 (CC BY-NC).

Furthermore, M. Ku et al. (7) analyses the characteristic regarding the wearability of the lens. When you want to make an intelligent contact lens you must also think about its softness and in order not to damage the cornea its components (such as the sensor, antenna, NFC chip, capacitor and resistor) must be integrated electrically with extensible and non-rigid interconnections. It is important to underline that the softness of the contact lens and its curvature could lead to a breakdown of the rigid materials that are conventionally used for integrated electronic systems, and this could lead to damage to the cornea or eyelid. In their approach, they tried to create a soft contact lens with highly transparent and stress-adjustable hybrid geometries in order to minimize breakage. The contact lens is designed with flat islands in which the rigid components of the system can be allocated (for example the cortisol sensor, the NFC chip, the capacitor and the resistor). It is then composed of elastic joints in order to maintain the curvature of the lens in which a transparent antenna and interconnection electrodes are placed. The optical polymer SPC-414, EFiRON, was used to make the rigid segments as it is thin and photomodable. For the elastic parts, on the other hand, a silicone elastomer (Elastofilcon A, CooperVision) was used, typically used for the manufacture of contact lenses.

S. Agaoglu et al. (5) try to look for an alternative to insert metallic or semiconductor components (used for power, radio frequency or Bluetooth communication, and data processing) required for the electrical measurements in wearable sensors which is a problem for ocular applications. The reason for their study is dictated by the fact that the air has a low permeability, the electronic components are opaque and it is also difficult to interface the sensor with the cornea and for these reasons they decided to study microfluidic sensors. The latter do not require the integration of any type of electronic element and also have various advantages such as transparency, biocompatibility, flexibility that are perfect for wearable applications. Therefore, comparing them with electric sensors, the latter have better comfort and air permeability.

However, the use of microfluidic sensors loses its advantages with the development of flexible and wearable electronics which have developed a lot thanks to the arrival of nanomaterials, such as metallic nanowires, graphene or transition metals dichalcogenides. In fact, nanomaterials have excellent mechanical and electrical characteristics and can thus be used for flexible electronics (24).

Nanomaterials show superior flexibility for flexible electronics implementation, have a wide range of surfaces, making them candidates for various applications. Furthermore, conductive networks based on one-dimensional nanomaterials can be used for flexible and transparent electronic applications which can provide good conductivity and transparency and also have excellent mechanical strength, as shown in Figure 11.

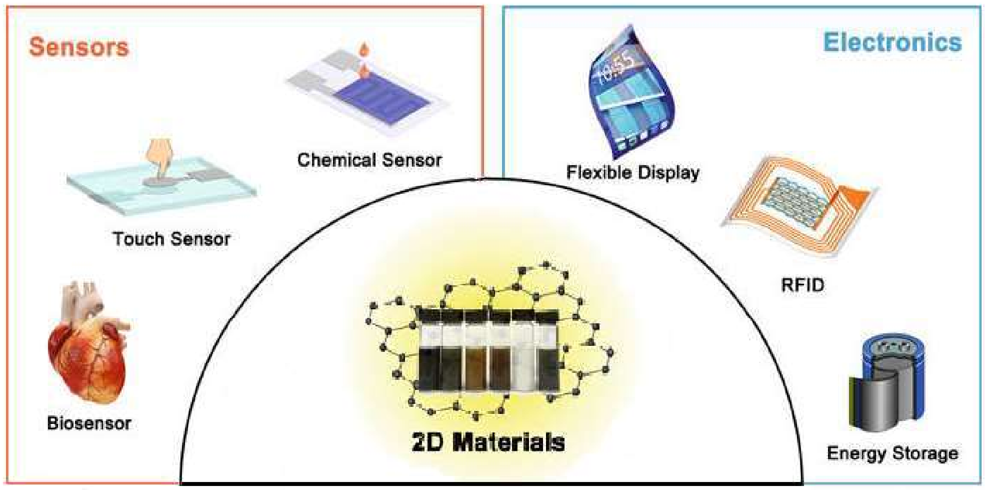

Figure 11: 2D Materials Technologies.

Graphene is a 2D nanomaterials and it is the material that we choose to analyze and to use for our project. An advantage of graphene is that its effective lattice mass is close to 0 as its two-dimensional lattice suppresses charge carrier backscatter. Secondly, graphene has a good optical property due to its transmittance of about 97% in the visible regime. It is perfect for our purpose, the use of graphene for the contact lens can allow for flexible and transparent electronics. Another important aspect of graphene is its production, it can be fabricated over a large area using various techniques such as CVD or a technique that consists of a process using a solution of reduced graphene oxide. Therefore, conventional top-down manufacturing technologies are possible for the fabrication of graphene devices. Thanks to these advantages, many studies have been carried out on the use of graphene in various applications in electronic systems. Park and others (24) reported several studies using graphene.

The first study analyzes flexible / stretchable GFET transistors in which an ionic gel is inserted into the graphene channel of the FET and is used as a dielectric layer for the gate. In GFETs, the drain and source electrodes are composed of three layers of graphene to improve conductivity. The materials listed above used for the realization of the FET arrays, are endowed with intrinsic flexibility and elasticity. Thanks to these properties they can be deformed in length up to 5% of deformation. The development of a flexible and extensible system made with GFET technology can be used for flexible logic circuits, such as inverters. The effectiveness of graphene can be increased with the use of AuNP in electrochemical sensors. Furthermore, the sensors are built in the form of wearable devices and their data can be sent and verified wirelessly (via a smartphone).

Another advantage of graphene is its good chemical stability and large surface area due to its 2D nanostructures, so, many researchers have used it as electrodes for energy storage devices (eg, supercapacitors, batteries).

The thickness of the graphene is what allows flexibility.

A disadvantage of graphene is its limited electrical resistance, limits its use in high-performance electronics. This behavior is due to graphene nanostructures, which consist of a monolayer or, at most, a few layers. Unfortunately graphene has another important disadvantage, due to the its absence of a bandgap it cannot be used in a digital applications.

For this reason, to overcome the limitations of graphene, like the degradation of its electrical properties due to the resistance between layers, and mechanical limitations, a hybrid structure can be realized with the combination of one-dimensional nanomaterials (like: CNTs or metal nanowires) with the bi-dimensional graphene and so different hybrid structures were investigated.

An advantage of a hybrid structure is that one-dimensional nanomaterials enhance the flexibility while bi-dimensional nanomaterials improve the electrical properties, such as low contact resistances, by removing empty gaps. Furthermore, these two nanomaterials can electrically connect to each other. For example, the AgNW/graphene hybrid films, used by Park et al. (24) showed resistance against electromigration and chemical stability against the oxidation of the AgNWs. Since the component materials have a high mechanical life, the electronics that have been manufactured could be properly fabricated on smart contact lenses and could be used solidly.

CHAPTER 2

SMART CONTACT LENS FOR COVID-19 DETECTION

2.1 Smart Contact Lens Design

The main idea of this work is to make a smart contact lens capable of detecting the Covid-19 in human tears. This type of technology could be very useful in detecting this disease and could also help stop its continuous spread.

Unlike the well know test used for the detection of covid-19, which required bulky medical equipment, with our device the patient can be under control during his daily life without any stress. For this reason is important to develop a study in the direction of wearable devices for health monitoring.

Our system consists of four subsystems: sensing GFET with selective aptamers, power rectifier circuit, a transmitter circuit and an antenna, all integrated on a contact lens as seen in Figure 12.

The system has to work in contact with a human eye, therefore, to increase safety, no battery was included in the circuit design. The power is done with a 2.5 GHz input signal through the antenna.

The input signal is received by a rectifier which will supply the correct voltage to the entire circuit.

To detect the presence of covid-19 our aim is to use the chemical properties of graphene and aptamers that can select the specific virus. Aptamers are used to distinguish the coronavirus from all other chemicals present in tears.

To do this, we want to use the same principle based on Michael A. Stroscio's researches as (9), (10) and (11). In these three papers, several Graphene-Based Field-Effect Transistor Aptasensor used to detect different type of substances in human blood, skin or serological fluid are presented. M. Stroscio's first study (9) is used to detect Adenosine Triphosphate while in his second work (10) he presents an aptamers used for potassium detection. The third study of M. Stroscio (11) is used for the detection of Immunoglobulin E antibody for the analysis of allergic reactions.

Unlike these works we want to use the same theoretical principle with a different purpose, we want to detect the presence of Covid-19 in human tears.

The transmitter part consists of a cross-coupled LC oscillator and a power amplifier, which are used to convert the sensor's low-frequency output signal into a high-frequency signal capable of being transmitted with a small antenna size.

The output signal of our circuit will be twice the input frequency, 5 GHz and will be read by an external receiver.

2.2 GFET sensor for Covid-19

To detect Covid-19 in human tears we decided to use a circuit consisting of graphene field effect transistors and aptamers.

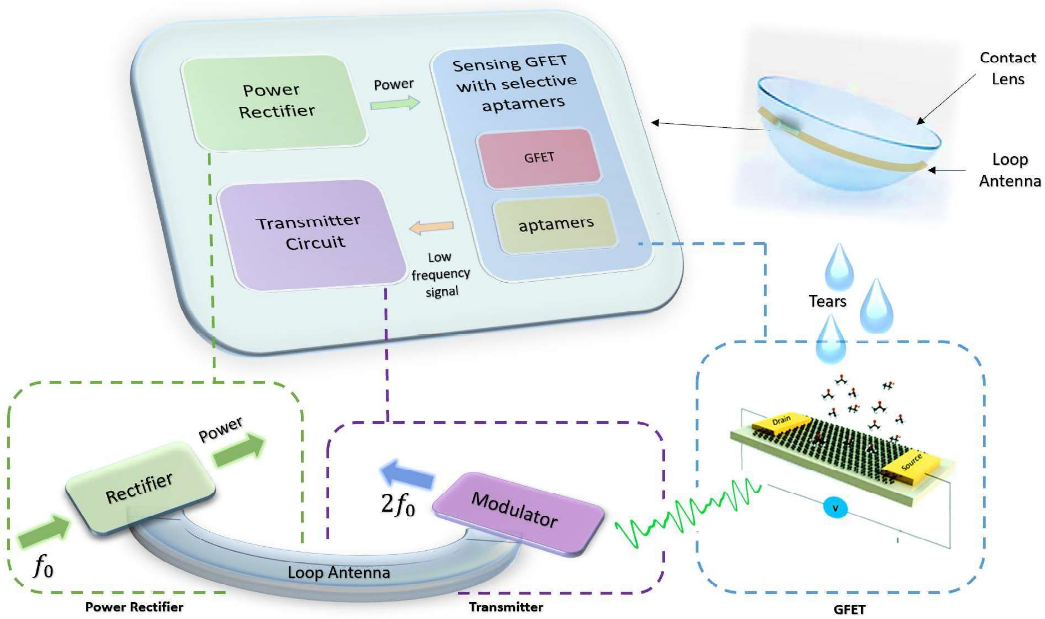

Figure 12: Smart contact lens circuit composed of sensing GFET with selective aptamers, power receiver, transmitter circuit and a loop antenna.

The use of graphene for the chemical analysis in fluids has already been studied in several researches such as (12), (13) and (14).

Hajizadegan M. et al (12) present a novel types of low interference self-powered wireless sensors based on graphene circuits, which may have a dual function: molecular-level chemical detection and radio-frequency (RF) modulation Figure 13. They also proposed a new reliable reading method capable of extracting the fluctuation and mean value of chemical doping levels in graphene field effect transistors based on machine learning. Their presented a graphene based harmonic sensor has the potential to take advantage of a wide range of sensing applications, including emerging wearable and implantable devices, and also real-time monitoring of chemical / gas exposures and biological agents.

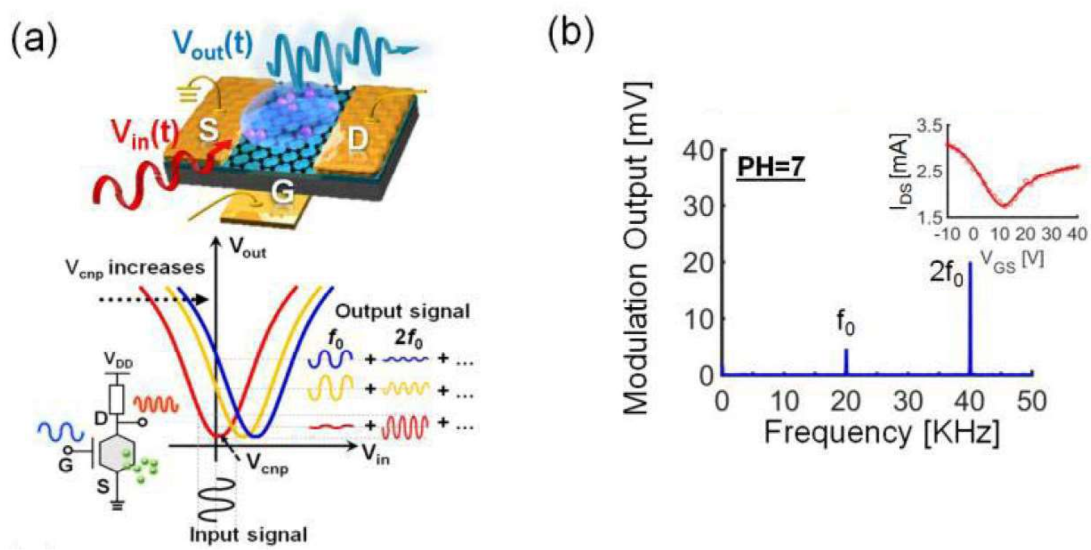

Figure 13: Schematics of a single-state GFET and its frequency modulation. This image is taken from the work of Hajizadegan M. et al. (12) in their Figure 4, 1558-1748 © 2017 IEEE.

Huang H. et al (13) report a new paradigm for detection modulators: a device made with GFET technology able to directly modulate the radio frequency electrical carrier signal when in contact with chemical agents, and able to have a memory of its electrochemical history. Through an experiment in which the frequency was modulated and at the same time the modulator was exposed to alternating cycles to air and ethanol or water treatment, it was possible to demonstrate the concept and implementation of this detection modulator based on graphene.

Shahini A. et al (14) propose the concept and design of a transparent, flexible, wireless and self-powered sensor made with graphene radiofrequency components integrated on a bio-compatible substrate. Their wireless sensor is made entirely of graphene. It has an optically transparent antenna made of graphene capable of receiving the fundamental frequency and retransmits the information detected at the second harmonic of the received signal. Doing so allows for a decrease in noise against a background of severe interference / clutter detected. Thanks to the quad-ring circuit of the GFETs the sensor is able to perform both the detection and the frequency modulation. This is possible thanks to the non-linear conversion gain which is chemically sensitive to exposures and chemical / molecular / gas agents. Versatile wireless sensing and Internet of Things applications such as smart contact lenses can thus take advantage of these battery-free and transparent sensors based on two-dimensional nanomaterials.

Unlike the works cited, our research is focused on the use GFET and aptamers. We decide to use aptamers to decrease the probability of false detections and therefore have more reliable systems. Unfortunately, the aptamers connected to GFET required a low frequency value to function properly and thus the design of the whole system is more complex than systems using high frequency GFET as presented in (12), (13) and (14).

2.3 Power, transmitter and receiver Circuit

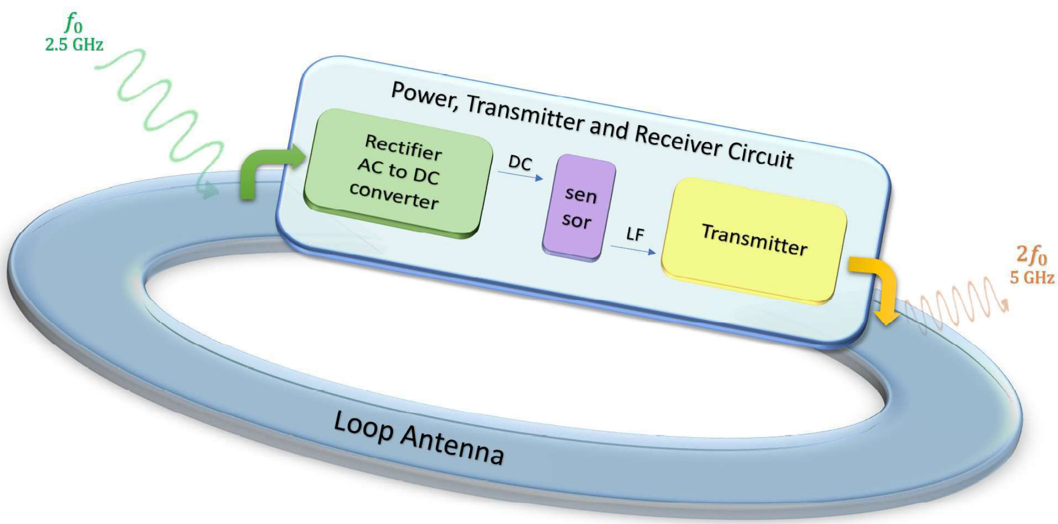

Figure 14: Smart contact lens Power, Transmitter and receiver circuit.

In our project we want to create a circuit that must be integrate on a contact lens and therefore, for this reason, several aspects must be verified. The circuit must be suitable for the fit, so comfort and safety must be checked. The size of the circuit must be limited to avoid damage to the cornea and not to cover the patient's visibility region. Furthermore, it must be safe and therefore the use of a battery in a wearable device is strongly discouraged. This is why we decided to make a circuit without battery. The power is performed by the antenna with a 2.5 GHz signal. The band used is in the ISM band and complies with the safety regulation for wearable devices. The signal received by the antenna is transmitted to a power rectifier which converts the AC signal into a DC signal suitable for powering the other circuits in the device.

For the transmitter part, Figure 15, we have designed a circuit capable of taking the low frequency signal at the sensor output and transforming it into a high frequency signal. To build this circuit we carried out a study in literature to analyze different designs of a similar circuit used in wearable devices (15), (16), (17), (18), (19).

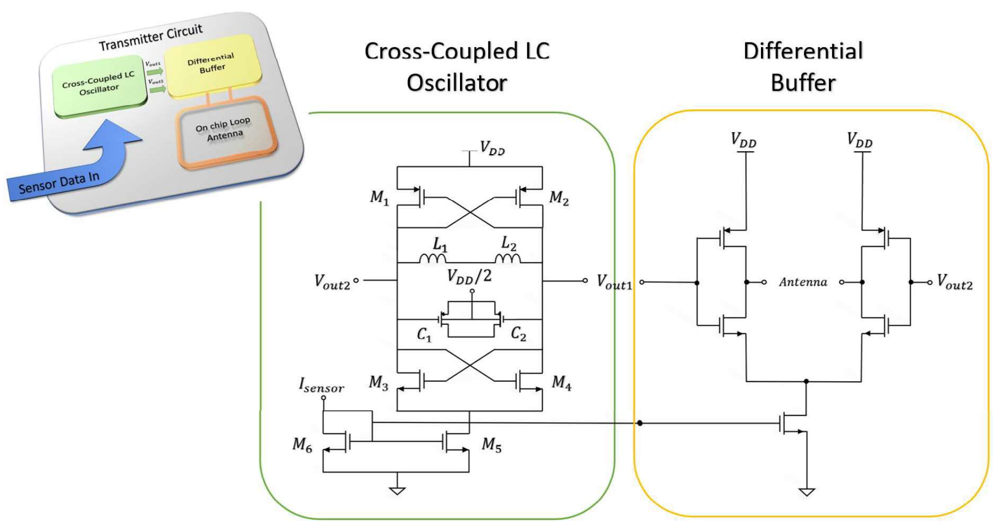

Figure 15: Transmitter circuit design composed of an Cross-Coupled LC Oscillator and a Differential Buffer.

2.4 Antenna

In our research we need to use an antenna capable of receiving a 2.5 GHz signal and transmitting one at 5 GHz but no larger than a contact lens. In addition, the antenna must be stretchable because the contact lens surface is not flat and must also ensure the visibility.

For all these reasons we have decided to use a transparent antenna realized by Erricolo et al.. Transparent antennas that provide spatial extensibility and a more usable area than traditional opaque antennas have become a lively and exciting pursuit in the age of 5G communications, as they can be seamlessly integrated with wearable devices.

They make a flexible transparent linear-dipole rectenna designed with metal-dielectric nanocomposite. The measured responses of their antenna confirm the feasibility of making flexible, conformal and transparent high-performance antennas for various 5G applications that require a very large numbers of antenna elements to improve connectivity and data transmission rate.

CHAPTER 3

TRANSMITTER

3.1 Transmitter Design

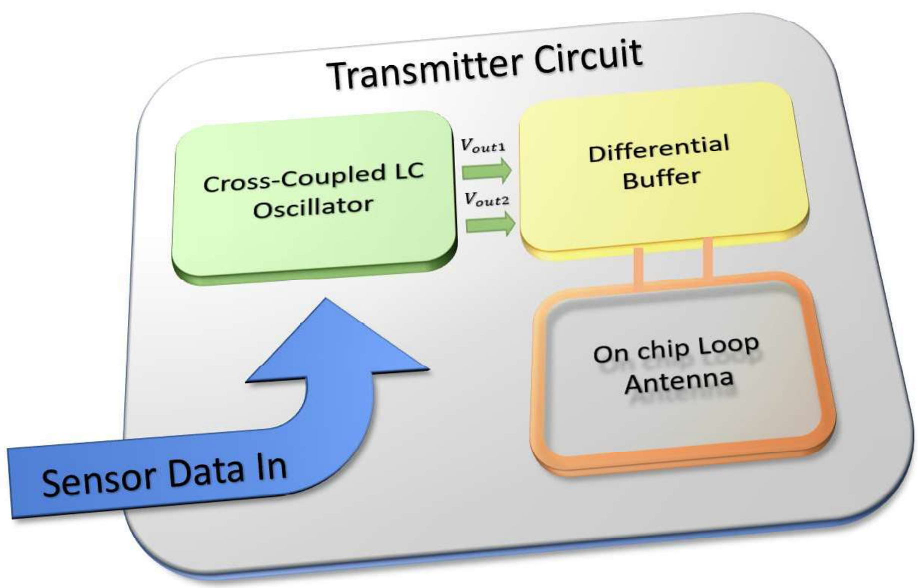

Figure 16: Smart contact lens Transmitter circuit composed of an Cross-Coupled LC Oscillator, a Differential Buffer and the Loop Antenna.

3.1.1 Analysis of transmitter circuits already utilized in wearable devices

The different transmitter models in literature must be small and capable of transmitting high frequency signals due to the growing development of Internet of Thing technology.

The spread of this kind of devices has forced to reduce the size of the overall circuits implemented on it, include antennas. For this reason, frequency band required to be transmitted is increased in the order of GHz given the relationship between lambda (the wavelength) and the diameter of the antenna.

Our work focuses on a wearable device that needs to be applied to a contact lens. This positions adds many restrictions to circuit design because our smart contact lens do not have to damage the cornea. Taking these considerations into account, we need to make a transmitter that is thin, small in the area so as not to obstruct the visual field, compatible with a PET substrate and with reduced consumption due to the absence of a battery. All the parameters we need to satisfy are present in the Table I.

To carry out our project we studied several literature researches on up link circuits in biomedical devices such as (16), (20), (18), (19).

Wearable devices required compact radios without batteries and an integrated on-chip antenna to enable miniaturization. Both power and data must be transmitted through the antenna, eliminating the crystal and I/O pads. In addition, any accumulation of on-chip energy (such as large capacitors or inductors) is precluded by the ultra-small area of the die; therefore, sufficient power must necessarily be provided wirelessly.

TABLE I: TRANSMITTER PARAMETERS REQUIRED BY THE PROJECT

Transmitter Specifications	
substrate type	PET
thickness	$< 400\ \mu m$
width	$< 3\ mm$
length	$< 3\ mm$
power consumption	$\sim 1\ mW$
power supply	3.3 V
input current	10 μA
input frequency	10 kHz
output frequency	5 GHz

Consequently, two major challenges need to be overcome for uplink communication which are highlighted by the study of Zhao B. et al. (20). First, the uplink communication signal is blocked due to the wireless power tone, which results in a poor signal to noise ratio (SNR) uplink. Furthermore, the oscillator may be subjected to additional noise due to the absence of the crystal degradation of the uplink SNR.

In their research, Zhao B. et al. (20) explained how to detect counterfeit electronics using an RFID system by addressing design challenges with the proposed two-color technique. The "dielet" radio chip has an overall size of 116 µm × 116 µm and is manufactured with 65 nm CMOS technology, which is free of battery, pads and crystals.

Another research group, Jeon C. et al. (18), unveiled a controller IC integrated into an intelligent contact lens used for wireless telemetry. Their proposed transmitter is capable of dual-mode operations with a single external loop antenna. The first operating mode proposed is that of Load-Shift Keying with wireless backscatter, the antenna is used as an inductor for magnetic resonance coupling with this transmitter configuration. The second operating mode of the transmission is that of radio frequency, RF, in which its configuration becomes that of an active LC oscillator circuit. The configuration used in our project is the same used in the design approach presented in this research. In addition, with a controlled timing schedule they applied a 0.2 % duty cycle to suppress average power consumption, minimizing static power consumption in sleep mode.

With the stringent constraints of contact lens environments, circuitry technology for wireless communications was critical in enabling part of the controller IC. In literature there are several research that use the load-shift keying (LSK) backscattering thanks to its near-zero power consumption during data transmission. However, with an LSK type transmission the reader has to transmit a strong electromagnetic power to the coil as the magnetic resonance coupling between two inductive coils is used. This feature presents a bottleneck if you want to use LSK to continuously monitor ocular applications.

For this reason, we decide to not use the load-shift keying for our contact lens and we decide to adapt the same solution used by Jeon C. et al. (18). Indeed, to achieve real-time monitoring without position constraints or strong EM power generation one solution could be to use RF transmission radiated from the EM field. This is possible by using an integrated power amplifier inside the smart contact lenses. Furthermore, to allow the user to carry a reading system, the communication of the RF transmission could reach a distance of a few meters.

In their research Jeon C. et al. (18) feature an intelligent contact lens controller chip capable of performing two modes of use by means of a pad option set by an external path to supply voltage or ground. In their intelligent contact lens system the data is constantly monitored through the transmission of RF which is powered by a thin film battery. The transmission is carried out via a wireless telemetry system requested via LSK and during data transmission it is powered by wireless charging. The chip consists of a transmitter capable of providing both LSK and RF data transmission, as seen in Figure 17.

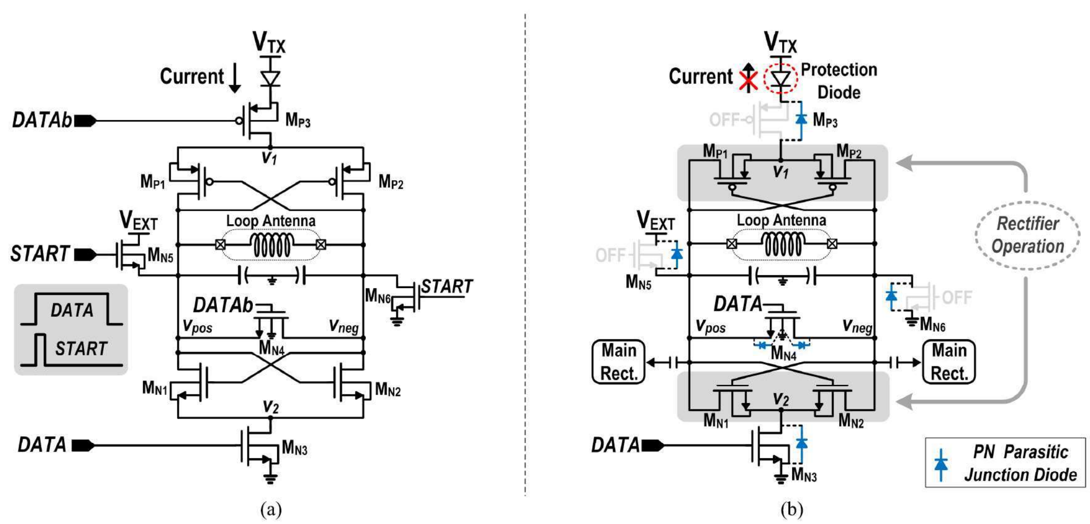

Figure 17: Proposed dual-mode transmitter circuit configured for (a) RF and (b) LSK modes. This image is taken from the work of Jeon C. et al. (18) in their Figure 3, 0018-9200 © 2019 IEEE.

Unlike our project, we decided to perform only one mode, radio frequency data transmission, with a circuit design very similar to the one they utilized.

Another study on a very small transmitter was conducted by Merenda M. et al (19),who have made a transmitter that implements an on-off keying modulation (OOK) with standard 3.3 V 0.35 μm CMOS technology, and are designed to be subjected to duty cycle. The transmitter type uses a cross-coupled complementary LC oscillator as in our work. Furthermore, to maximize the power delivered to the radiating element, coupling networks are used, placed between the antenna and the power amplifier. In their transmitter, to power the small loop antenna was implemented a simple source coupled differential amplifier as shown in Figure 18.

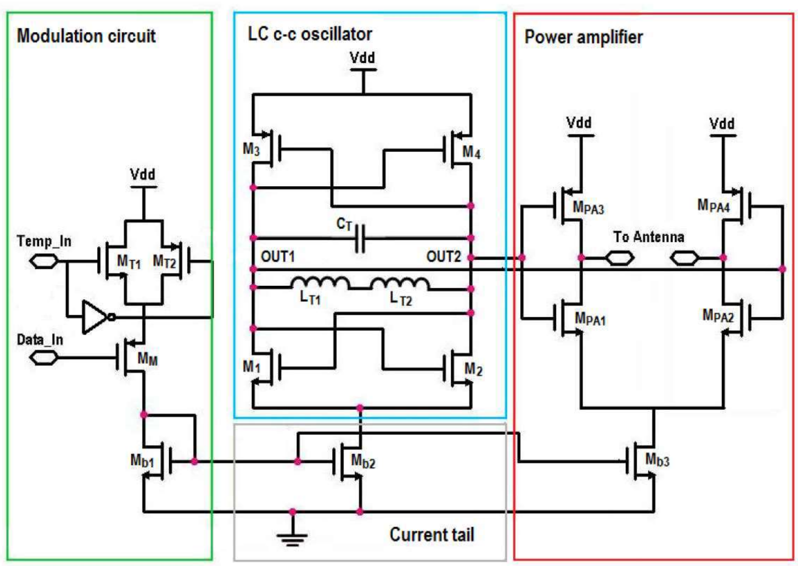

Figure 18: Circuit schematic of LC c-c Oscillator-based transmitter. This image is taken from the work of Merenda M. et al. (19) in their Figure 2, © 2019 by the authors (CC BY).

3.1.2 Transmitter Design utilized in our work

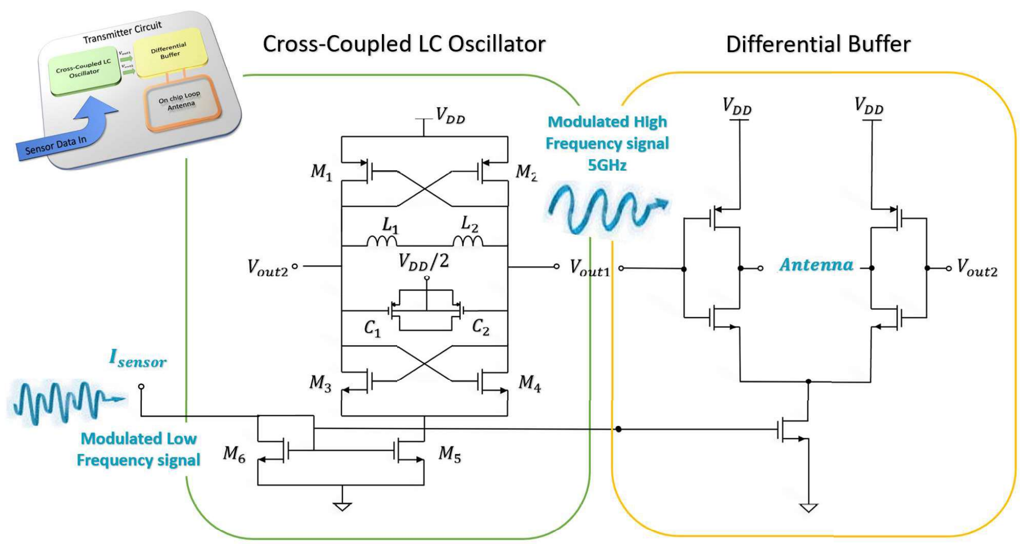

Figure 19: Cross-Coupled LC Oscillator used to convert the Low Frequency signal sensor output in a High Frequency signal, at 5 GHz to be transmitted by the loop antenna.

After an analysis of the existing transmitter circuit we have designed our own model according to the specifications (visible in Table I) that we must guarantee to integrated it into the smart contact lens.

Our transmitter, Figure 19, must take a low frequency input signal from the GFET and aptamers sensor and convert it into a high frequency signal capable of being transmitted with the small loop antenna designed for the project.

The input signal can almost be considered a DC signal because its frequency is on the order of 10/100 kHz which is five orders lower than the 5 GHz transmitter output signal.

However, we must be able not to lose the information carried by the input signal and send it to an external receiver.

The main idea to allow this is to use the dependence of the output signal on the current injected in the base. We decided to use a current mirror circuit on the base of the oscillator to duplicate the information signal on its base.

We decided not to connect the antenna directly to the oscillator output but to insert between them a power amplifier such as the research group of Merenda M. et al (19) and of Jeon C. et al. (18). Indeed, to achieve real-time monitoring without position constraints or strong EM power generation one solution could be to use RF transmission radiated from the EM field. This is possible by using an integrated power amplifier inside the smart contact lenses. Furthermore, to allow the user to carry a reading system, the communication of the RF transmission could reach a distance of a few meters. Furthermore, placing the coupling networks between the antenna and the power amplifier serve to make the power delivered to the radiating element maximum.

3.2 LC cross-coupled Oscillator

Wearable devices such as our contact lens required very small devices to be comfortable dressed, so the diameter of the loop antenna could not exceed 1 cm. Thanks to this we have to create a circuit capable of converting the low frequency signal output of the sensor that has the information in a high frequency signal that can be transmitted by our small antenna.

To make our up-link circuit we need a very small circuit not longer than 3 mm to ensure patient visibility. Furthermore, it must be attachable to PET substrate used in our smart contact lens.

For all these reasons, we decided to use an LC cross-coupled oscillator to convert the information signal into a high frequency signal. This type of approach had already been used by Merenda et al. in their research (19).

Unlike our work, Merenda et al. (19) used the oscillator to convert the information to a frequency of 2.5 GHz while in our work an output frequency of 5 GHz is required.

Our choice of transmitting the 5 GHz output signal is driven by the choice of 2.5 GHz for the frequency of the power carrier which ensures the safety of wearable devices. Hence, we have decided to use a frequency that is twice the frequency of the power carrier.

A big advantage in using this specific output frequency is the GFET ability to act as a high frequency doubler circuit. Unfortunately, we have decided to used aptamers to detect the presence of the covid-19 virus which required a low frequency signal. We have decided to go down this path because we have decided to give more importance to reducing the probability of false detections rather than to the complexity of the circuit.

Driven by this idea we need a circuit capable of transmitting information at 5 GHz and we decided to design a LC cross-coupled oscillator to do this task.

The ideal tuning curve for an oscillator is given by Equation 3.1:

$$\omega = \frac{1}{\sqrt{LC}} \tag{3.1}$$

However, the ideal tuning curve differs from the one of an LC tuned voltage controlled oscillator. Also, if we use varactor instead of capacitor, full swing oscillation is applied directly across them. The capacitance value is function of the voltage, C(V), and the tuning curve becomes highly dependent on the oscillator bias current. An estimate of the tuning curve for MOS-varactor tuned VCOs is provided in the research of Levantino S. et al. (25).

To convert the low frequency signal of the sensor output we decided to use the varactor theory. In practice, if we have an amplitude of oscillation, the tuning interval turns out to be lower than that of the ideal characteristic. Due to this mechanism, a dependence is created between the output frequency and the amplitude, which in turn is a function of the bias current. This mechanism thus creates a conversion from an amplitude to a frequency modulation and is typical of any oscillator topology that adopts a steep varactor as seen in Figure 20 b.

An additional effect occurs in all VCO topologies with differential cross-coupling in which the bias current acts on the bias level of the varactor. The output common mode level is modulated by the low frequency noise given by the bias current and therefore by the bias voltage of the varactor. Hence, a change in the varactor bias causes the frequency modulation, Figure 20 a.

So, if we have the bias current equal to the sensor output current thanks to this theory, we can get a modulation function of the sensor current that carries our information.

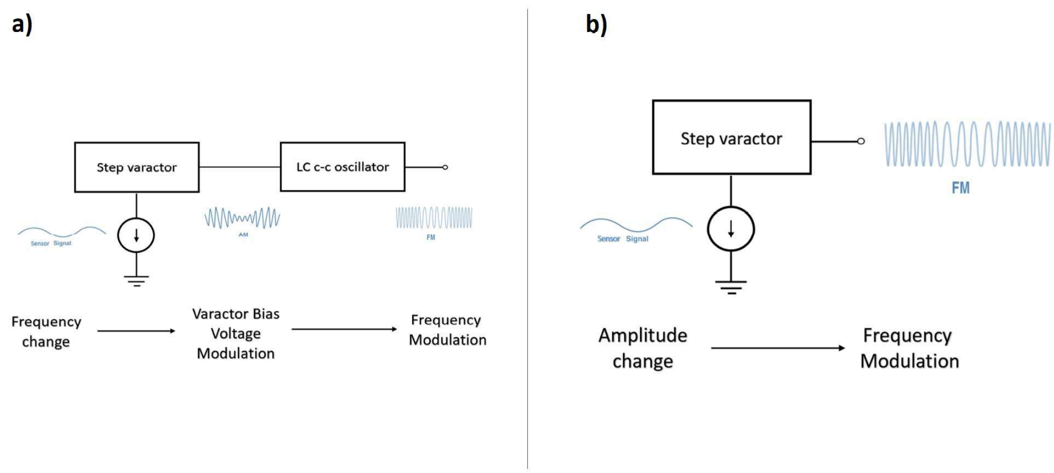

Figure 20: Tuning curve deviations from the ideal characteristic driven by the sensor signal.

3.2.1 Oscillator parameters

Figure 21 shows the schematic of our 5 GHz oscillator. Being a low frequency application it is preferable to use a double cross-coupled transconductor. This operates in the current limiting regime and with respect to the single-pair structure it exploits the bias current µA with doubled efficiency. The oscillator can be manufactured with CMOS technology 0.35 µm. We decided to design it with LT-Spice and we used the ECEN4827/5827 library, a modified library for use with LT-Spice a 0.35 µm CMOS process to characterize both the PMOS and NMOS of our circuit.

The power supply is set to 3.3 V, that is required by the CMOS technology.

Inductors can be designed as spiral inductors in the physical realization of the circuit, in the simulation software we utilize two 3.7 nH inductors. We decided to use two inductors instead of one at 7.4 nH to maintain a balance differential circuit. In fact, it is possible to rise the resistance of the tank with the use of two inductors in series and therefore the oscillation of the output voltage for a given bias condition. The capacitance is consituted by the capacitance of the varactor which is centered in a range that allows an oscillation at 5 GHz. In fact, if we want to use the ideal formula of the tuning curve to have a first idea about the oscillation frequency with two inductors a 3.7 nH and a 137 nF capacitor we get from Equation 3.2 and Equation 3.3:

$$\omega = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{(3.7\ nH + 3.7\ nH)(137\ nF)}} \tag{3.2}$$

$$f = \frac{\omega}{2\pi} = 5\ \mathrm{GHz} \tag{3.3}$$

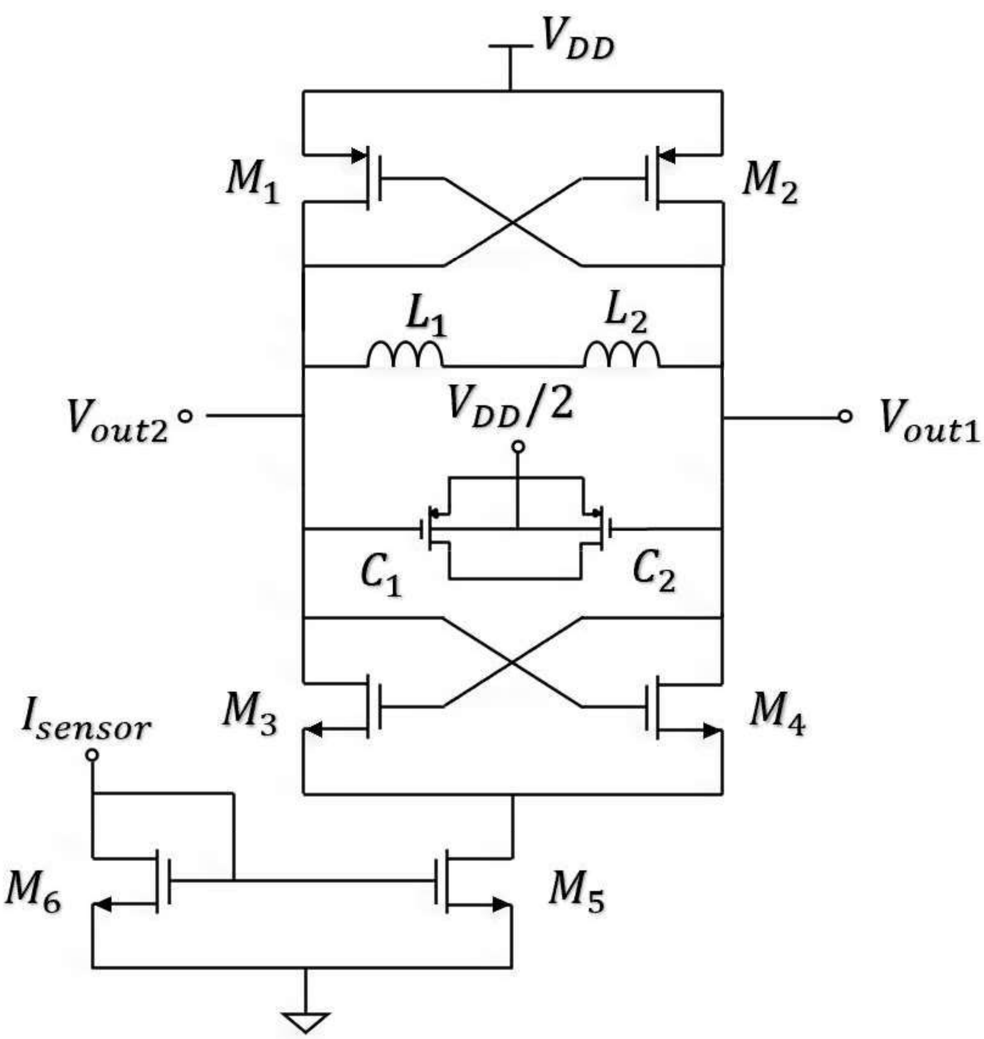

Figure 21: Cross-Coupled LC Oscillator used to convert the Low Frequency signal sensor output in a High Frequency signal, at 5 GHz to be transmitted by the loop antenna.

3.3 Power Amplifier

The power amplifier circuit is placed between the LC cross-coupled oscillator and the antenna. The circuit is important in obtaining the required power transfer to the antenna. Furthermore, by positioning the coupling networks between the power amplifier and the antenna, it is possible to maximize the power delivered to the radiant element as used by Merenda et al. (19).

In our transmitter, a differential amplifier was coupled to the source to power the small loop antenna. The circuit design is presented in Figure 22 to the oscillator and was DC coupled with its and guaranteed enough output voltage swing to switch the amplifier.

To understand how the circuit works, suppose that in Figure 22 V_{out2} is at the maximum voltage value, while V_{out1} is at the minimum value. In this case, the PMOS connected with V_{out2} is turned on and feeds some current into the antenna. On the other side of the system, the NMOS connected with V_{out1} is turned on, allowing the current flowing through the loop structure to be grounded. Vice versa when V_{out2} is at the minimum voltage value, while V_{out1} is at the maximum one.

If we analyzed the formula that gives the theoretical maximum power transmitted to the antenna. So, the following theoretical maximum power can be transmitted to the antenna Equation 3.4 we get a total power of 26 μW, -91.7 dB. The value is reached with a voltage supply, V_{dd}, of 3.3 V, ideal value of the saturation voltage of the MOSFET, V_{sat}, of 0.7 V and a sensor current of 10 μA.

$$P_{antenna} = (V_{dd} - V_{sat}) * I_{sensor} \tag{3.4}$$

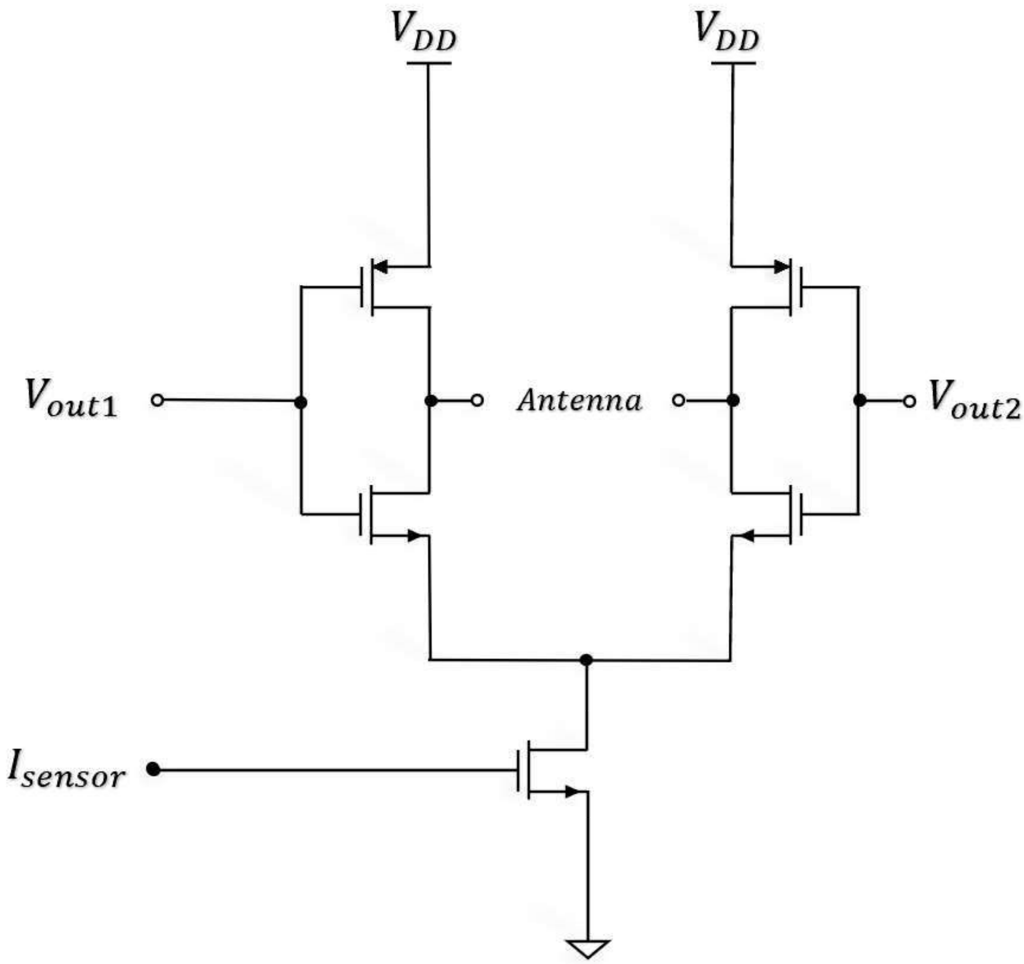

Figure 22: Power Amplifier used to obtain the required power transfer to the antenna.

CHAPTER 4

TRANSMITTER SIMULATION

4.1 Simulation Results

The transmitter that we want to design consist of an LC cross-coupled oscillator used to convert the sensor low frequency in 5 GHz high frequency signal and a power amplifier used to obtain the required power transfer to the antenna.

First, we want to analyze the LT-Spice diagram of the cross-coupled oscillator that is the most complex circuit of the transmitter.

Then, we analyze the LT-Spice diagram of the power amplifier and in conclusion we describe the overall transmitter circuit composed of the two diagram presented before.

4.2 Oscillator LT-Spice Design

To analyze the LC cross-coupled oscillator that we have decided to use for our smart contact lens we used the LT-Spice program.

We said that the size of our transmitter is very important because it has to be integrated on a contact lens so it has to ensure the specifications of Table II.

Figure 23 shows the schematic of our 5 GHz oscillator designed with LT-Spice and it uses a double cross-coupled transconductor. Compared to the single-pair structure, it exploits the bias current μA with doubled efficiency, operating in the current limiting regime. The oscillator is made in CMOS technology 0.35 μm and we used the ECEN4827 / 5827 library, a modified

TABLE II: TRANSMITTER SIZE SPECIFICATIONS

Transmitter Size Specifications

thickness	< 400 μm
width	< 3 mm
length	< 3 mm

library for use with LT-Spice a 0.35 μm CMOS process to characterize both the PMOS and NMOS of our circuit.

The power supply is set to 3.3 V, that is required by the CMOS technology.

Inductors can be designed as spiral inductors in the physical realization of the circuit, in the simulation software we utilize two 3.7 nH inductors. We decided to use two inductors instead of one at 7.4 nH to maintain a balance differential circuit. In fact, it is possible to rise the resistance of the tank with the use of two inductors in series and therefore the oscillation of the output voltage for a given bias condition.

The sensor output current is designed in LT-Spice with a current generator. The current generator is set to realize a sine wave with amplitude 10 μA and a frequency of 10 kHz because this is the output that we expected form the covid-19 sensor.

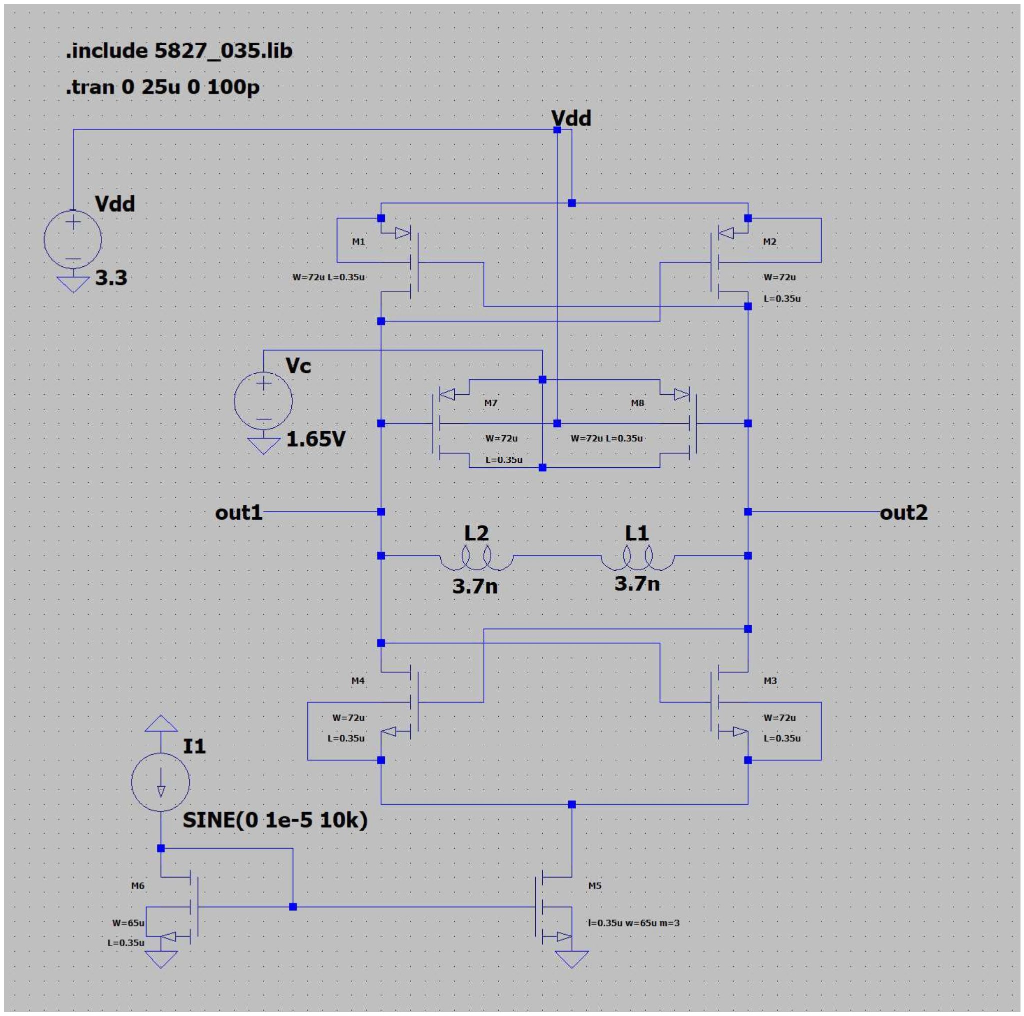

Figure 23: LT-Spice design of the LC cross-coupled Oscillator with varactor implementation used in the transmitter circuit of the Smart Contact Lens.

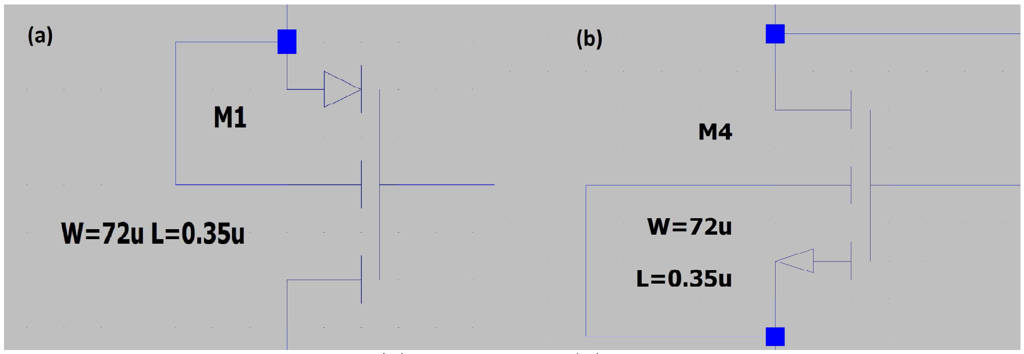

Figure 24: LT-Spice design of the (a) PMOS and (b) NMOS used for the LC cross-coupled Oscillator.

4.2.1 CMOS Technology

For our purpose we have decided to utilize 0.35 µm CMOS for the design of our oscillator. This kind of CMOS was already used by Merenda et al. (19) in their work where they realize an integrated circuit with size: 2480 µm x 2480 µm.

An other work that highlights the wearability of our design is given by the study of Jeon C. et al. (18) where they used 0.25 µm CMOS.

In their work, a 0.23 µm-thick PET substrate is prepared with gold patterning and also in our work we want to use a PET substrate so we do the assumption to have the same substrate thickness also in our design.

Then, the unoccupied substrate area is removed by laser cutting and all discrete components are glued to it with chip flip. Using a silicon elastomer the contact lens is manufactured covering all areas except the detection area. The thicknesses of all their components are controlled within 0.2 mm.

For our project we have to ensure the same specifications of Jeon C. et al. (18) so we have decided to use the same approach and realize a 0.23 µm-thick PET substrate with the thicknesses of all components are controlled within 0.2 mm. This ensure that the circuit could be integrated in a contact lenses because they have thickness of roughly 0.4 mm.

Thanks to this study in literature, we decided to design the oscillator with the 0.35 µm CMOS technology utilizing the ECEN4827/5827 library, a modified library for use with LT-Spice a 0.35 µm CMOS process to characterize both the PMOS and NMOS of our circuit as seen in Figure 24.

4.2.2 Varactor Technology

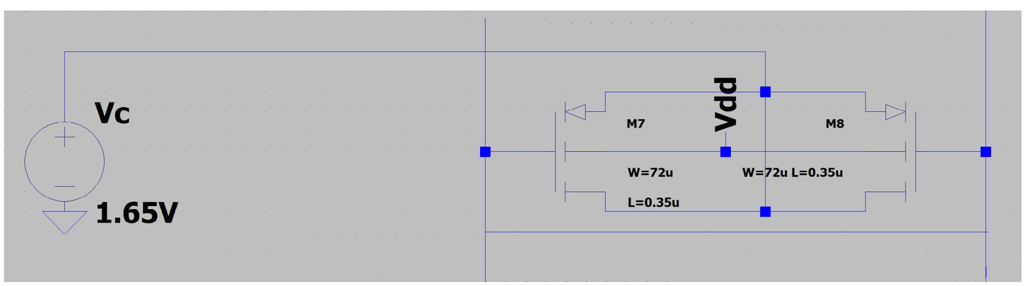

Figure 25: LT-Spice design of the capacitor is realized with a varactor system composed of two PMOS used for the LC cross-coupled Oscillator.

To realize the LC tank of our oscillator we have decided to use a MOS varactor structure instead of two capacitors.

Different variations of varactor exist with MOS structure: D=S=B (PMOS transistors with drain source and bulk connected together), I-MOS (inversion-mode MOS), A-MOS (accumulation-mode MOS).

For our work we decided to utilize the I-MOS structure where the basic structure is identical to a PMOS and for this reason we use the same 0.35 μm CMOS model used before, this structure was also used by Bunch et al. in their work (21). In this configuration, the source and drain are short-circuited together to form one terminal of the capacitor while the polysilicon gate is used to form the other terminal as seen in Figure 26 (a). However, at the higher voltage available in the circuit, V_{dd} is connected to the majority (n-well) of this structure. Furthermore, the device can only operate in inversion mode since the n-well connection of the device is at a potential equal to or greater than the gate. This produces the CC / small signal C-V characteristic shown in Figure 26 (b).

4.2.3 Inductor Technology

In the design of our LC cross-coupled oscillator we can make two choices for the inductor circuit: 1) we can decided to use the antenna like the inductor to reduce the transmitter size on the smart contact lens or 2) we can decided to use spiral inductors that otherwise increase the area of the integrated chip.

We decided to use the second option analyzed before because after a study of already existing research, as the one of Merenda et al. (19) and Bunch et al. (21), it is visible that the dimension of the transmitter circuit respect the required specifications for the realization of the smart contact lens also adding the inductors in the design.

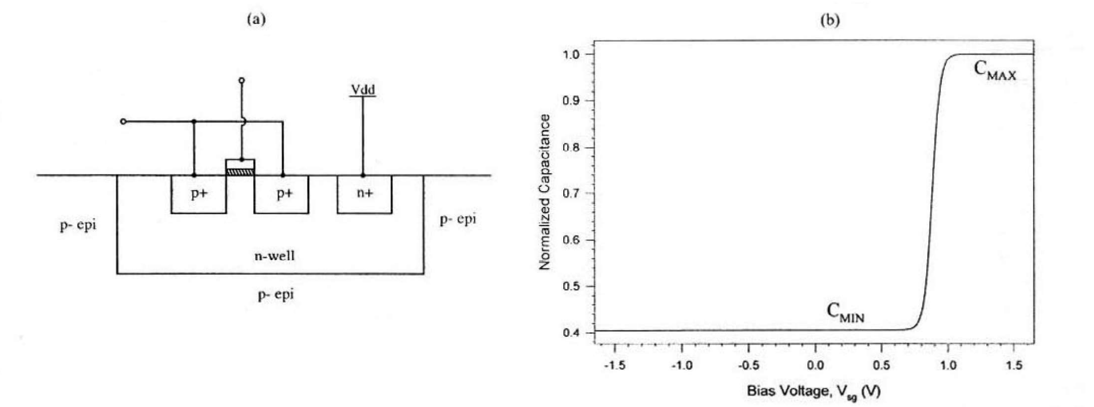

Figure 26: (a) Inversion MOS structure (b) inversion MOS C-V curve. this image is taken from the work of Bunch et al. (21) in their Figure 2, © 2003 IEEE

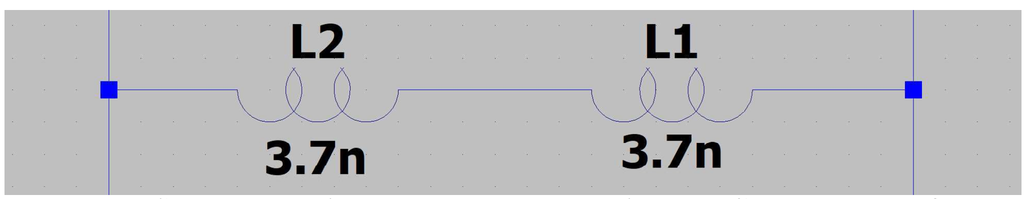

Figure 27: LT-Spice design of the two inductors used for the LC cross-coupled Oscillator.

An advantage of using spiral inductors instead the self antenna is given by the possibility to add a power amplifier in the circuit and so in obtaining the required power transfer to the antenna. Furthermore, it can maximize the power delivered to the radiating element.

For the design of the oscillator we decided to use two inductors of half the required value to obtain the correct frequency oscillation instead of one for mantaining a balance differential circuit.

In Figure 27 is visible the LT-Spice design of the two inductors used in the LC cross-coupled circuit.

4.2.4 Oscillator LT-Spice Results

In this sections we want to show the output signals obtained with our design.

First of all we analyzed the output signal of the LC cross-coupled oscillator to verify that it is a sinusoidal signal at 5 GHz.

In Figure 28 is visible the simulation output that correspond with the expected result.

In Figure 29 is visible the Fast Fourier Transform of the signal and the output frequency is correctly 5 GHz.

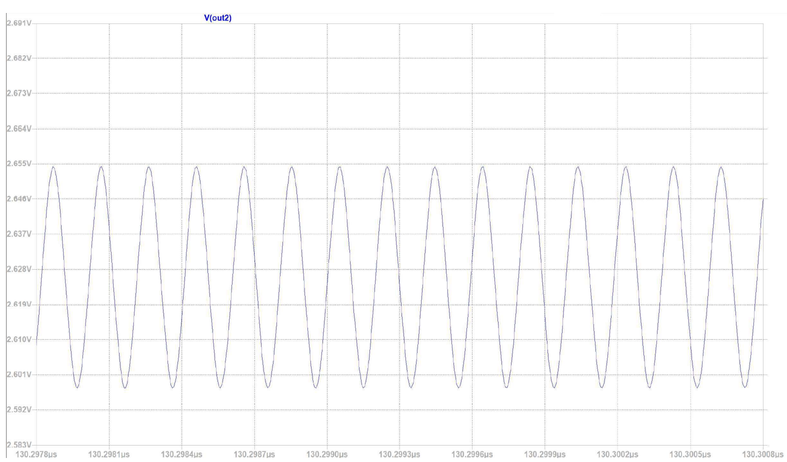

Figure 28: Output signal of the LC cross-coupled oscillator.

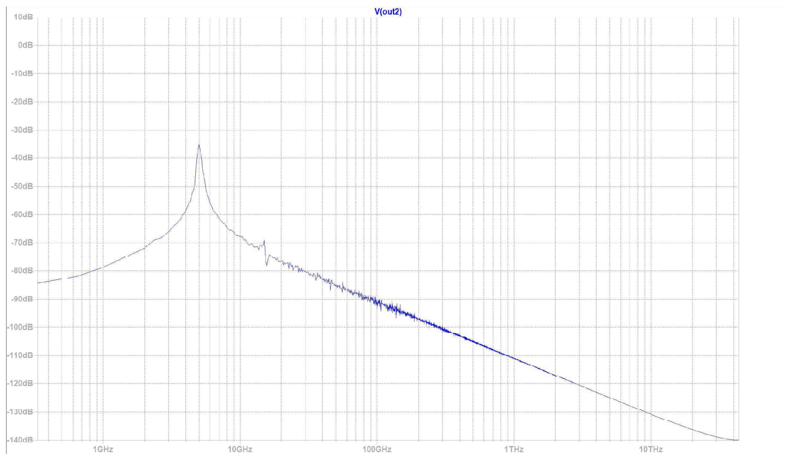

Figure 29: Fats Fourier Transform of the 5 GHz output signal of the LC cross-coupled oscillator.

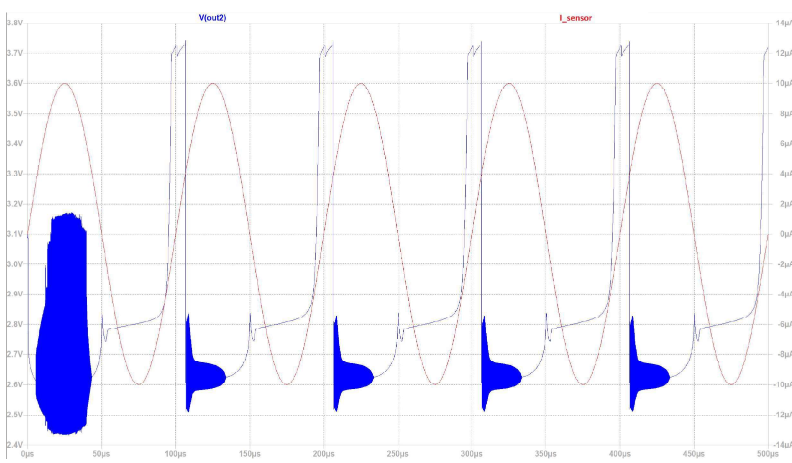

Figure 30: Comparison between the output signal of the Cross-coupled LC Oscillator, V(out2), and the input signal coming form the sensor, I_sensor.

After this analysis we have analyzed the output signal in function of the input sensor current which brings the information.

In Figure 30 is visible that the output signal at 5 GHz is able to bring the information of the input signal with an amplitude modulation.

In Figure 31 is present the Fast Fourier Transform of both the two signal and we want to underline the presence of a pick at 10 KHz also for the output signal. This result correspond to the expected output signal that is able to transmit the sensor information thought the antenna.

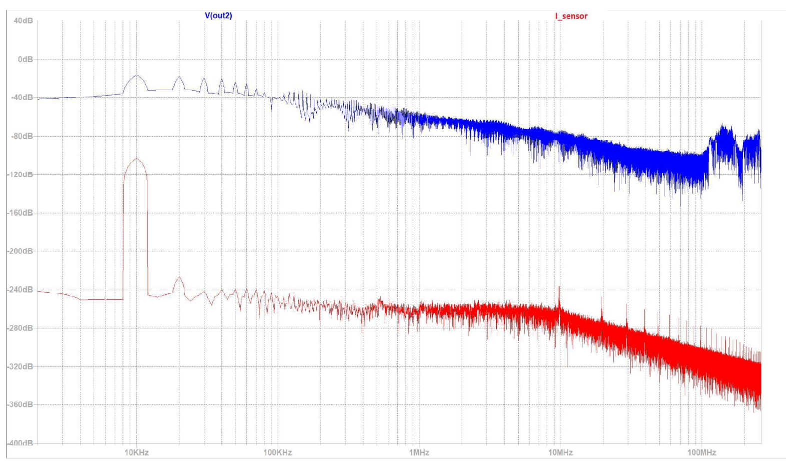

Figure 31: Comparison between the Fats Fourier Transform of the output signal of the Cross-coupled LC Oscillator and the input signal coming form the sensor.

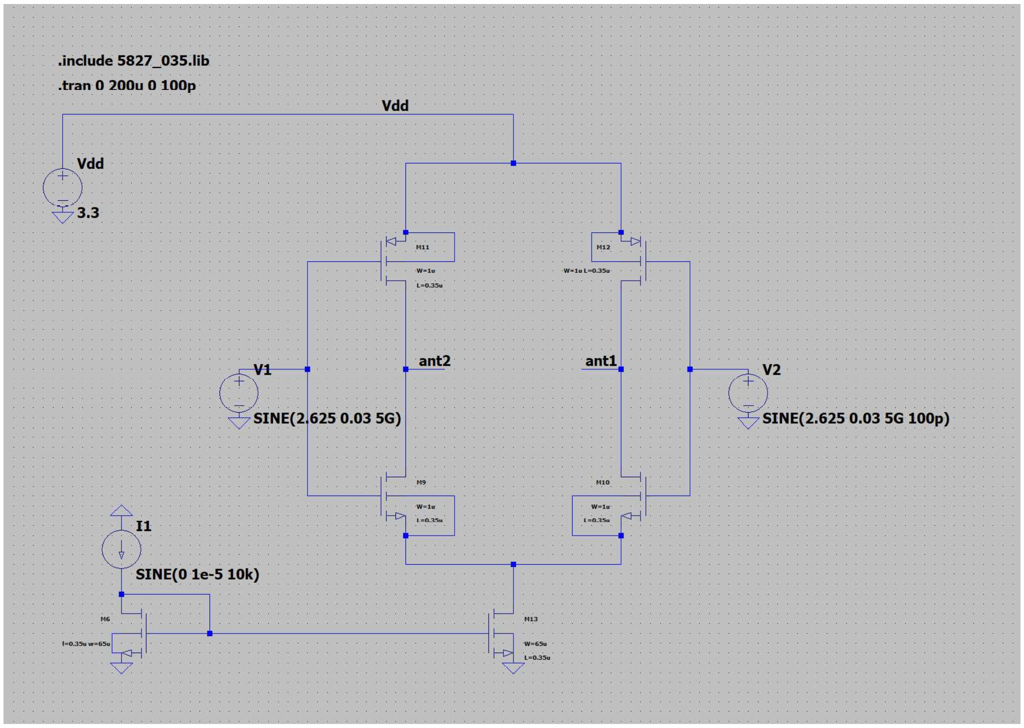

Figure 32: LT-Spice design of the Power Amplifier implementation used in the transmitter circuit of the Smart Contact Lens.

4.3 Power Amplifier LT-Spice Diagram and Results

The power amplifier circuit is placed between the cross-coupled LC oscillator and the antenna. The circuit is important in obtaining the required power transfer to the antenna. Furthermore, the power delivered to the radiant element is maximized by inserting the matching networks between the power amplifier and the antenna as used by Merenda et al. (19).

In our transmitter, to power the small loop antenna was implemented a simple source coupled differential amplifier. The LT-Spice circuit design is presented in Figure 32 where we designed the cross-coupled LC oscillator output with two voltage generator at 5 GHz frequency, phase shifted of 180 degree, with 30 mV amplitude and offset of 2.625 V. We decided to use this value because they are the specifications of the Cross-Coupled LC Oscillator anayzed in the section befor and visible in Figure 28.

The CMOS implemented in the power amplifier are 0.35 μm CMOS as the one used for the cross-coupled LC oscillator designed in LT-Spice utilizing the ECEN4827/5827 library, a modified library for use with LT-Spice a 0.35 μm CMOS process to characterize both the PMOS and NMOS of our circuit.

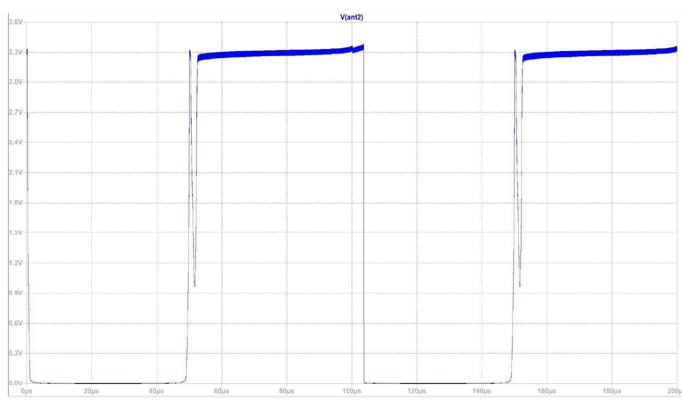

Figure 33: LT-Spice simulation of the output signal of the Power Amplifier implementation used in the transmitter circuit of the Smart Contact Lens.

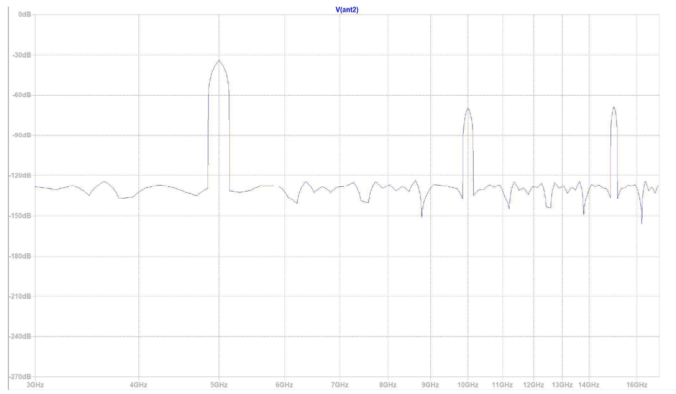

Figure 34: Fast Fourier Transformation of the Power Amplifier implementation showing the output signal with the presence of oscillation at 5 GHz

4.4 Transmitter LT-Spice Diagram and Results

In this section, the Cross-Coupled LC Oscillator and the Power Amplifier designed are merged together to realize the complete Transmitter Circuit used for the Smart Contact Lens.

We designed the Transmitter with LT-Spice using the ECEN4827/5827 library, a modified library for use with LT-Spice a 0.35 μm CMOS process to characterize both the PMOS and NMOS of our circuit as seen in Figure 24.

The inputs of our circuit are the sensor current, I_{sensor}, a 10 μA 10 kHz sinusoidal current, a supply voltage, V_{dd}, of 3.3 V and a control voltage, V_c, of half the supply voltage.

The sensor current, I_{sensor}, is the input of a current mirror where the other extreme is on the foot of the oscillator and on the foot of the power amplifier.

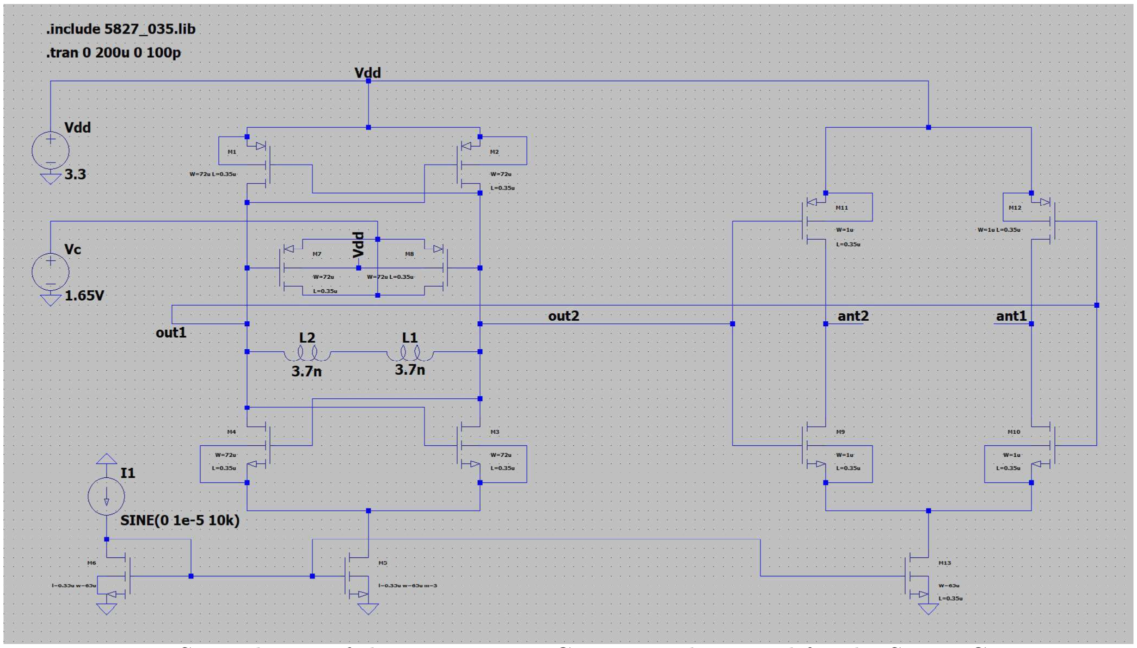

Figure 35: LT-Spice design of the Transmitter Circuit implemented for the Smart Contact Lens.

The supply voltage, V_{dd}, is used to power the oscillator and the power amplifier and it is connected with the PMOS of the two circuits.

The control voltage, V_c, is used for control the varactor structure composed of I-MOS, its value is chosen to be half of the supply voltage to obtain a maximum tuning range of the cross-coupled oscillator. We are able to obtain the maximum tuning range if in the middle of the available tuning voltage range, usually $V_{dd}/2$, is set the transition point of the curve (25).

So, the transmitter circuit has three input, one given by the sensor and two given by the rectifier.

Then, the transmitter has two output, in the LT-Spice design visible in Figure 35 called $ant1$ and $ant2$. The output $ant2$ is shown in Figure 36 compered to the sensor current where the modulation of the output given by the information input is visible. These two output signal are at 5 GHz frequency and a zoom in the simulation figure is performed to see the oscillation.

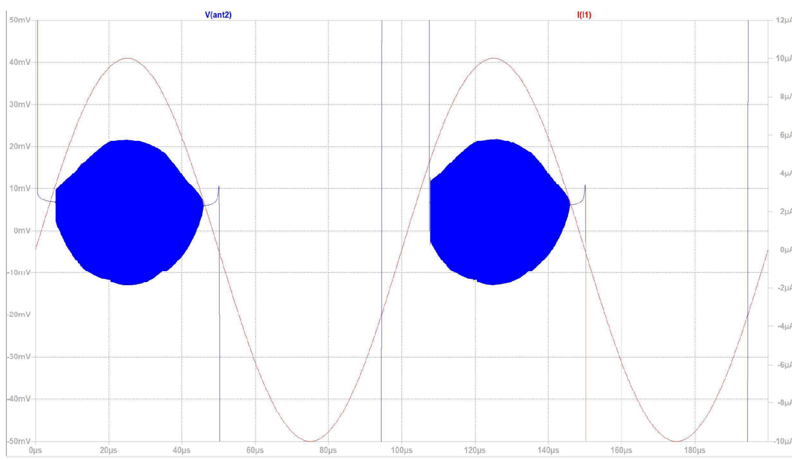

Figure 36: LT-Spice simulation of the Transmitter Circuit implemented for the Smart Contact Lens showing the output signal, V(ant2), and the input sensor current, I(I1).

In Figure 37 is visible the oscillation of $ant2$ output in blue and the $ant1$ output in red. The shape of the waveforms can be physically explained as described by Levantino et al. (25). The capacitance of the capacitor increases when the voltage signal drives the capacitor towards the storage region and thus the period of oscillation slows down. When the depletion region is

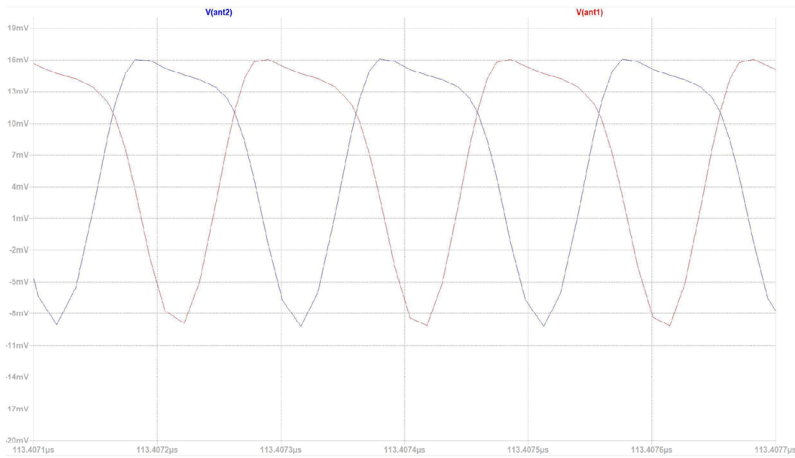

Figure 37: LT-Spice simulation zooming the output signals ant1 and ant2 of the Transmitter Circuit implemented for the Smart Contact Lens.

reached the varactor, the capacity is lowered and the period is shortened. The balance of the charge in Equation 4.1 gives rise to a different amplitude of the positive and negative peaks with respect to the dc value, where V_{WG} is the voltage between the well and the gate, $V_{out2,max}$ is the maximum value of the voltage output of the oscillator, $V_{ou1,min}$ is the minimum value of the voltage output of the oscillator and $C(V)$ is the value of the varactor capacitance in function of the voltage.

$$\int_{V_{WG}}^{V_{WG}+V_{out2,max}} C(V)dV = \int_{V_{WG}-V_{ou1,min}}^{V_{WG}} C(V)dV \tag{4.1}$$

At each peak, the maximum value of one capacity is reached while the other reaches its minimum. By the law of conservation of charge, the voltage peaks are different. A small peak quantity corresponds to a high capacity and vice versa. The first and second harmonic concentrates most of the power of the waveform. Furthermore, the second harmonics of the two waveforms are in phase, while the first two harmonics are 180 out of phase. So the output of the oscillator composed only of the first harmonic at 5 GHz because it is the differential one.

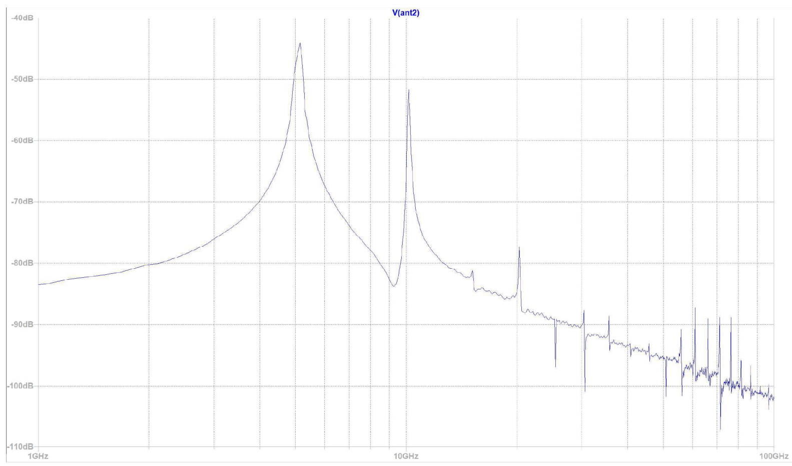

Figure 38: Fast Fourier Transform showing the frequency of the output signal of the Transmitter Circuit implemented for the Smart Contact Lens.

CHAPTER 5

PROPOSED TRANSMITTER FABRICATION

5.1 Transmitter physical designed

In this section we want to explain how to make the transmitter fabrication that we designed with LT-Spice in the previous sections.

Keeping in mind the most important part of the project which is its environment, a contact lens, we have to create a circuit suitable for the context.

A contact lens is not a rigid substrate in which a circuit could be designed, it is flexible, curved and exposed to tears.

In literature, various researches on integrated circuit on contact lens are presented different research and we report here the main researches relevant to the study of our work.

Joen C. et al. (18) present a smart contact lens IC controller manufactured using 0.18 μm CMOS, thus different from our work that uses 0.35 μm CMOS. They used gold stud bumps sit on all the pads for the integration on the contact lens surface through flip-chip bonding as seen in Figure 39 (a). A 0.23 μm-thick PET substrate is prepared with gold patterning. Then, the unoccupied substrate area is removed by laser cutting and all discrete components are glued to it with chip flip. Using a silicon elastomer the contact lens is manufactured covering all areas except the detection area as seen in Figure 39 (d). The thicknesses of all the components are controlled within 0.2 mm which is less than the thickness of the contact lens of 0.4 mm as seen in Figure 39 (e). The backside of the IC is grinded.

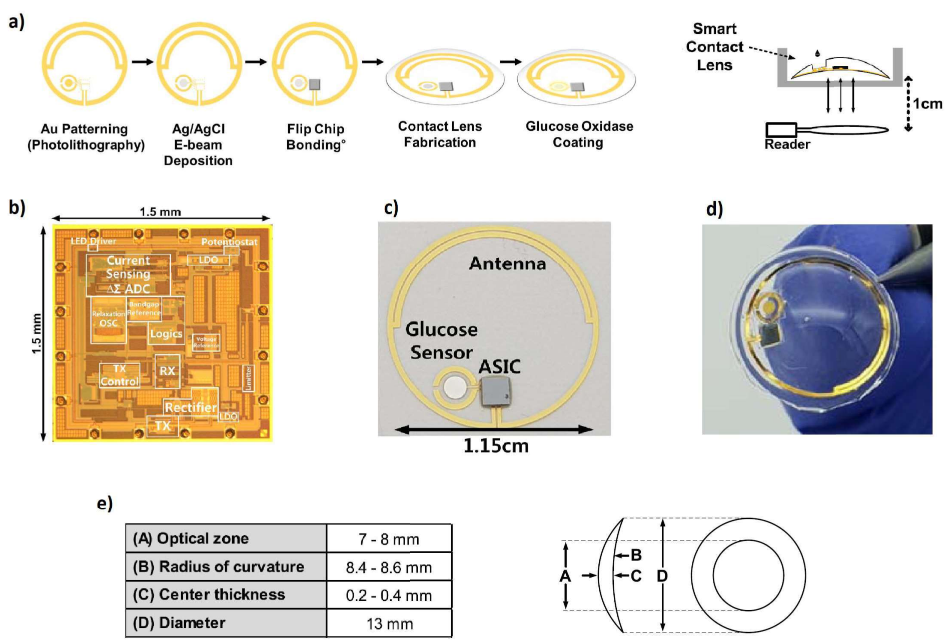

Figure 39: Fabrication procedure and implemented SCL systems for RF data transmission. This image is taken from the work of Joen C. et al. (18) in their Figures 12, 21 and 22, 0018-9200 © 2019 IEEE.

For their design, Joen C. et al. (18) decided not to use new flexible technology for the transmitter circuit but to use a 0.2 mm thick chip that has been integrated onto the contact lens due to its small size.

For our project we can decide or to follow the path of Joen C. et al. and we make the circuit in the same way or we can make a flexible and thickener circuit.

For this purpose an other research was studied, that of Vilouras A. et al. (22). They have not specifically studied a smart contact lens like us or Joen C. but they explain how to make CMOS model devices and circuits on flexible ultra-thin chips.

Thanks to their study we can implement a transmitter chip on the smart contact lens with a thickness really lower than that of Joen C., of about 140 μm so 3/4 than Joen C. chip.

Using well-established grinding technique the fabricated chips were thinned down to 20 μm. Then, the thinned chip was integrated on flexible printed circuit boards (PCBs).

Vilouras A. et al. (22) fabricated 0.35 μm chips with a thickness of about 480 μm. However, it is not possible to bend these chips because they must have a bulk silicon thickness close to an ultra-thin regime, less than 50 μm. For this reason it is necessary to obtain a reduction in thickness. It can be achieved by physical thinning after the stress relieving step which offers a rapid material removal rate and provides thin and smooth silicon. In particular, a widely established technique can be used which consists in the use of abrasive particles and incorporated grinders and rear grinding is done. In the work of Vilouras A. et al. the dicing (DBG) was used before grinding to guarantee the maximum percentage of yield (22) as seen in Figure 40. The silicon die was partially diced by Half-Cut dicing tool along the dicing line and following this step, the thinned chip was packaged over 120 µm polyimide-based flexible PCB using ball to wedge wire bonding technique.

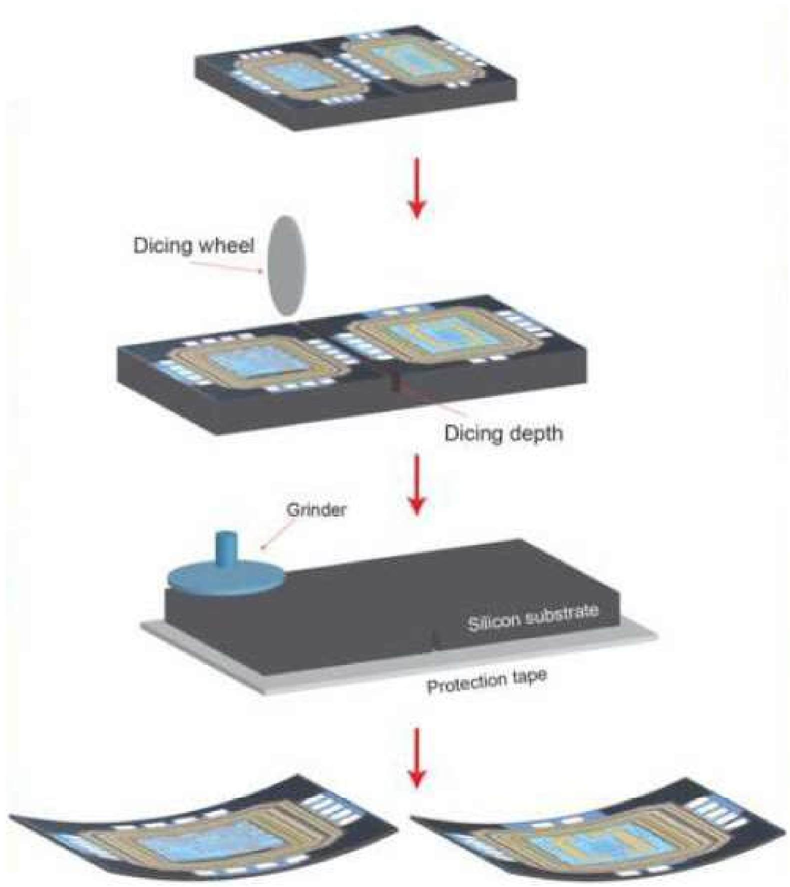

Figure 40: Illustration of thinning process using DBG postprocessing technique. This image is taken from the work of Vilouras A. et al. (22) in their Figure 2 d, © 2017 IEEE.

Finally, for the design of your transmitter we decided to use the technique explain by Vilouras A. et al. (22) to reduce the thickness of the 0.35 μm CMOS circuit and to make it flexible. Hence, it is more compliant to integrate on smart contact lens respect the work performed by Joen C. et al. (18).

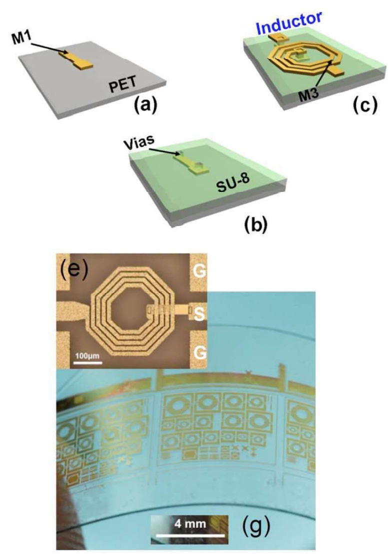

Figure 41: Fabrications steps for the flexible GHz inductor. This image is taken from the work of Sun L. et al. (26) in their Figure 1, © 2010 American Institute of Physics.

Furthermore, our circuit is also composed of two 3.7 nH inductors that allow the transmitter to operate at 5 GHz. For the realization of these two devices we have studied the work of Sun L.

et al. (26) where they presented how design flexible and small size inductors capable of operating in the GHz range. To manufacture the inductor, they started with optical photolithography on a PET substrate. Then they performed a electron-beam evaporation followed by a liftoff to deposit a 30/400 nm Ti/Au metal on the PET substrate. This first metal layer serves as the center lead metal of spiral inductors. Later, to make the spiral inductors they used a 1 μm SU-8 as the intermetal dielectric. To access the central metal lead of the inductors, it was spun onto the sample surface followed by a photolithographic modeling phase. Finally, a higher interconnection metal Ti/Au at 30 nm/1.5 μm was evaporated to form the metal spiral of the inductors and to make the interconnections. With this fabrication method, Figure 41, octagonal shape inductors were realized with a maximum thickness of 3.5 μm, perfect to be integrated on the smart contact lens.

After these analyzes, we know how to fabricate the two elements required for the design of the transmitter circuit, 0.35 μm CMOS and 3.7 nH inductors. Moreover, we understand how to realize them with a very small size in order to not obscure the field of view of the person and how to realize them flexible and with small thickness in order to not damage the cornea. Now we analyze how the circuit can be integrated in the smart contact lens. First of all we have decided to use the same idea of Joen C. et al. (18) and so to the flip-chip bonding for the integration on the surface of the contact lens the gold stud bumps sit on all the pads. The substrate is prepared with gold patterning on the contact lens and it is composed of a 0.23 μm thick PET. Then, the unoccupied substrate area is removed by laser cutting and all the discrete components are flip-chip bonded. The fabrication steps of our design are visible in Figure 42.

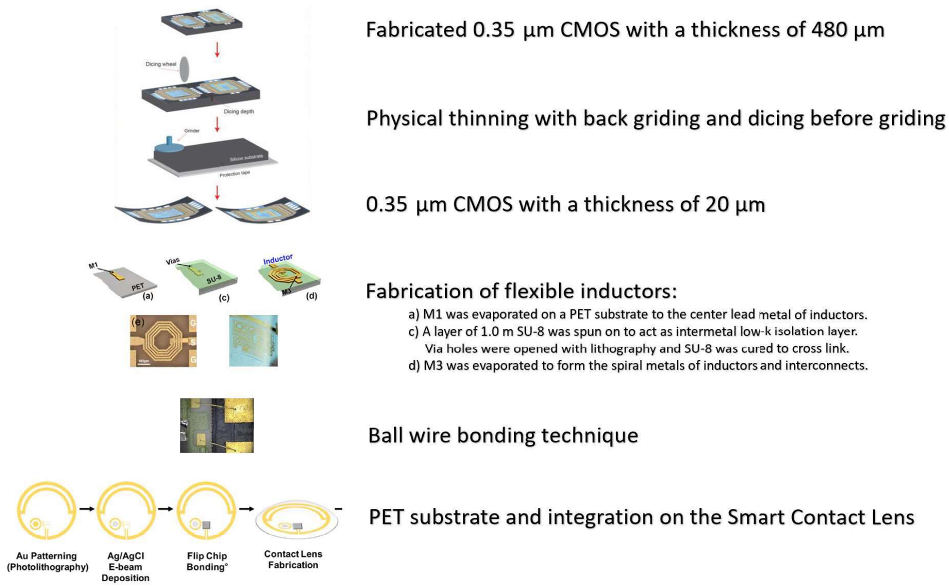

Figure 42: Steps required for the fabrications of our Smart Contact Lens. These images are taken from the works of of Vilouras A. et al. (22) in their Figure 2 d, © 2017 IEEE, Joen C. et al. (18) in their Figures 12, 21 and 22, 0018-9200 © 2019 IEEE, and Sun L. et al. (26) in their Figure 1, © 2010 American Institute of Physics.Sun L. et al.

CHAPTER 6

CONCLUSION

In conclusion, our project is focused on a new field of application for already used silicon circuit, as the CMOS used for the transmitter designed, and new kind of technologies, as the GFET used for the sensor designed.

The new aspect of this research is the study of a system cable of detecting the new covid-19 disease and so, to reduce its spread and help its fighting. This new disease is the reason of a lot of changes in human life and in his habits, so, we were moved to the motivation of decrease its danger and find a way to detect it in a easy and comfort way.

Already existing technique used for the detection of the virus are invasive, require time and healthcare personnel. For this reason, we are studying a new technique that can detect the virus in short time and able to analyze the person at any time and so to inform him in time if he has contract the virus. With this technology we want to decrease the spread of the pandemic.

This research is focused on the transmitter circuit integrated in technology used for the detection of the covid-19. In particular, this technology is a smart contact lens capable of analyzing the tears. It is composed by an antenna, a power circuit, a sensor and a transmitter circuit. To be able to design the transmitter of this wearable devices is important have understood the full circuits and how the block interact one to each other.

First of all, for the design of the transmitter we have analyzed already existing IC circuit used for the design of smart contact lens for the detection of other diseases. This was very important to understand how to guarantee the all specifications that we have for the system, as dimensions, materials, and flexibility.

Then, we have studied the other circuits required for the realization of the smart contact lens as antenna, sensor and power generator. After this analysis we have learned that the input of our circuit, the transmitter will be the information signal coming form the sensor with a frequency above 10 and 100 kHz and with an amplitude around 10 μA. With the analysis of the antenna and with a study regarding the frequency band allowed for the design of wearable circuit, we have decided to have an output signal at the frequency of 5 GHz.

So, with all these information we were able to design own transmitter circuit. We decided to used 0.35 μm CMOS circuit composed of a current mirror, a cross-coupled LC oscillator and a power amplifier. At the begin we designed all the circuits separately in LT-Spice and then we designed the complete circuit able to generate the desired output signal. After that, we studied new kind of technology fabrication to improve the integration of the system inside the smart contact lens. In the specific we analyzed new technique for flexible technology that we have decided to us in our project. The conceptual scheme of our design is visible in Figure 43.

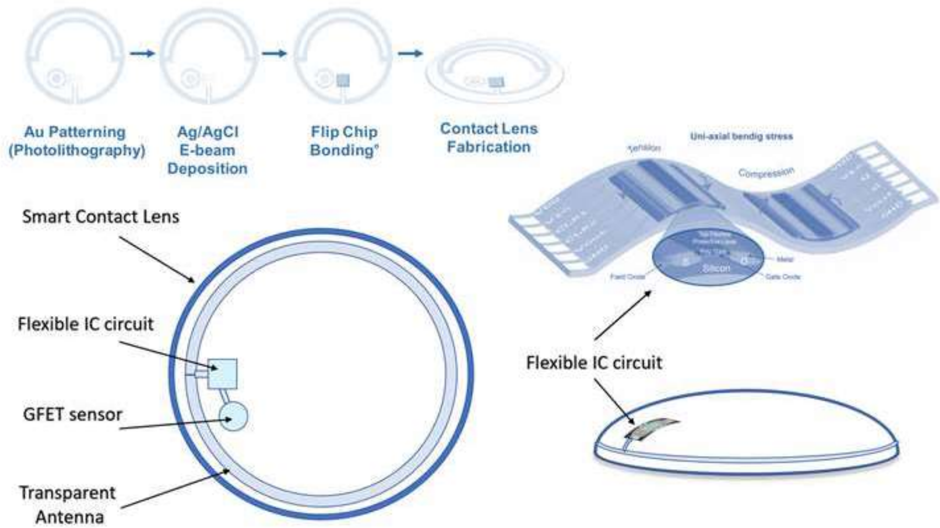

Figure 43: Fabrications ideas for our Smart Contact Lens. These images are taken from the works of of Vilouras A. et al. (22) in their Figure 1, © 2017 IEEE. and Joen C. et al. (18) in their Figures 21 a, 0018-9200 © 2019 IEEE.

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