Iby and Aladar Fleischman
Faculty of Engineering
Tel Aviv University

הפקולטה להנדסה
ע"ש איבי ואלדר פליישמן
אוניברסיטת תל-אביב

Project Work Plan

2896

Designing Oscillator for an Antenna at ∼3.5 GHz

Students:

Name: Nir Finch Cohen ID: 230336612

Name: Mazz Shaikh ID: 932056724

Project carried out at: Tel Aviv University

For the project instructor:

I approve the submission of the following report

Signature:

Name: Edoh Shaulov

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1 Abstract

In the ever-evolving landscape of wireless communications, the demand for efficient and reliable antennas operating at high frequencies has become paramount. This project delves into the implementation of an oscillator tailored for an antenna system at approximately 3.5 GHz. The oscillator is to be used in the transmitter antenna using a matching network. The significance of this endeavor lies in its potential to advance the performance of communication systems, catering to the ever-evolving landscape of modern connectivity.

The project delves into the field of Radio Frequency(RF) engineering, Microwave engineering and Analog Integrated Circuits. The intricacies of designing RF systems, especially those operating at high frequencies like 3.5 GHz, demand a meticulous understanding of circuit theory, analog circuits and frequency response, electromagnetic principles, and communication systems.

Oscillators are used in a diverse range of fields owing to their fundamental role in generating stable and precise periodic waveforms. The 3.5 GHz high-frequency oscillator to be developed as a part of this project finds profound uses in 5G networks and satellite communication. High-frequency oscillators are also used in radar systems for navigation, RFID tags in smartcards, and Magnetic Resonance Imaging (MRI).

In essence, the technologies harnessed in this project contribute not only to the advancement of 3.5 GHz antenna systems but also have far-reaching implications across industries, influencing the efficiency, precision, and reliability of diverse technological applications.

The project unfolds systematically, with each phase carefully crafted to ensure the successful realization of a high-performance 3.5 GHz oscillator. The implementation plan encompasses the following key stages:

1. Building an oscillator model
   The first step in the project starts by dealing with the 3.5 GHz oscillator. The model for the oscillator has to be tested using a Spice simulation.

2. Component Selection
   This step involves choosing the right transistor (NPN BJT/ NMOS) and then finding an available transistor that works in the interested frequency interval. A spice model has to be made for the chosen transistor and simulated using Cadence Virtuoso for S-parameters.

3. Antenna and it's matching
   The given oscillator design must have a matching network with the antenna we design. A matching network serves the crucial purpose of optimizing the transfer of power between two different components or systems that may have mismatched impedances. The primary use of a matching network is to ensure efficient power transfer and minimize signal reflections, particularly in the context of RF (Radio Frequency) and microwave systems.

4. PCB Layout
   Create a compact and well-optimized printed circuit board (PCB) layout, taking into account RF design principles to minimize parasitic elements and signal loss.

5. Testing
   The chip is tested with a pre-built receiver to check the integrity of the design.

The project implements the Transmitter block shown in (Fig 1)

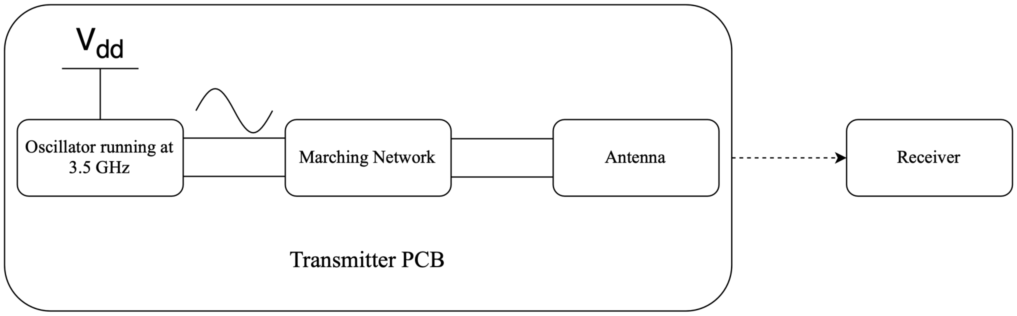


Figure 1: Block Diagram for project

2 Motivation

At the core of this project lies a needed scientific challenge – the demand for precise and stable oscillations at the 3.5 GHz frequency. This frequency band has emerged in modern wireless communication systems, playing a pivotal role in 5G networks, satellite communication, and various other applications.

From an engineering perspective, the project is motivated by the pressing need to enhance the efficiency and reliability of antenna systems operating at 3.5 GHz. The oscillator, as the fundamental component dictating the frequency of the transmitted signal, directly influences the overall performance of the communication system. The design and implementation of a bespoke oscillator for this frequency band involve considerations of frequency stability, phase noise, and power efficiency.

Current solutions for high-frequency use single-ended oscillators(Fig 2a), using MOS or BJTs. However, single-ended Colpitts has some issues as then tend to exhibit higher phase noise compared to differential oscillators. Phase noise is a measure of the randomness of an oscillator's output, and it can degrade signal quality in applications where precise timing is critical. They are also susceptible to common-mode noise, which can interfere with the desired signal. To tackle the problems with single-ended oscillators, differential versions of collpits oscillators have been proposed(Fig 2b) [**?**].

When operating at high frequencies, such as in the case of a high-frequency transmitter, the use of an off-the-shelf voltage-controlled oscillator (VCO) may fall short of meeting the stringent precision and frequency requirements demanded by the application. The design of a high-precision high-frequency transmitter necessitates a level of customization that generic VCOs may not afford. Thus, we build upon the two implementations stated above to have a more reliable system.

3 Statement of Work

3.1 Theoretical Background

3.1.1 S-Parameters

S-parameters, also known as scattering parameters, are a set of complex numbers that describe the linear relationships between waves entering and exiting a network of interconnected components. They are widely used in radio frequency (RF) and microwave engineering to characterize the performance of electronic circuits, antennas, and other devices. [?]

S-parameters are defined in terms of the incident, reflected, and transmitted waves at each port of the network. The incident wave is the wave entering the network, the reflected wave is the wave reflected back from the network, and the transmitted wave is the wave that passes through the network. The S-parameter matrix relates the phasors of the incident, reflected, and transmitted waves at each port.

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} & \dots & S_{1n} \\ S_{21} & S_{22} & S_{23} & \dots & S_{2n} \\ \vdots & & & \ddots & \\ S_{m1} & S_{m2} & S_{m3} & \dots & S_{mn} \end{bmatrix} \tag{1}$$

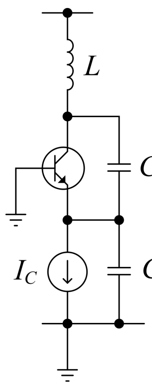
S-parameters are typically measured using vector network analyzers (VNAs). A VNA applies a small signal to one port of the network and measures the complex reflection and transmission coefficients at all ports. The measured S-parameters can then be used to characterize the network's performance. S-parameters play a crucial role for analysis of operating frequency and matching in the project.

The S-parameters of a network have several physical interpretations. The magnitude of S11, for example, represents the reflection coefficient at port 1. A value of 1 indicates perfect reflection, while a value of 0 indicates no reflection. The magnitude of S21 represents the forward transmission coefficient, which is the ratio of the phasor of the transmitted wave at port 2 to the phasor of the incident wave at port 1. A value of 0 indicates no transmission, while a value of 1 indicates perfect transmission.

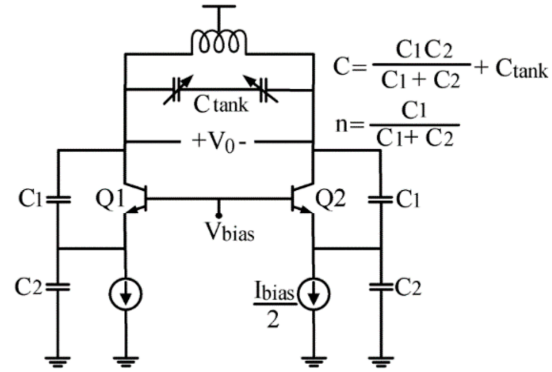
3.1.2 Collpits Oscillators

The Colpitts oscillator is a type of electronic oscillator that generates a sinusoidal waveform. It is a simple and versatile oscillator that can be used over a wide range of frequencies. The circuit consists of an inductor and two capacitors in parallel, which form a resonant tank circuit. The feedback for the active device is taken from a voltage divider made of the two capacitors. The oscillator is typically based on a bipolar junction transistor (BJT) or an operational amplifier (op-amp). It is also a very stable oscillator, which means that the frequency of the output waveform does not change much over time. This makes the Collpits oscillator a good choice for applications where frequency stability is important, such as radio transmitters and receivers.

Here is a simplified explanation of how a Collpits oscillator works: [?]



(a) Single-Ended Collpits Oscillator



(b) Differential Collpits Oscillator using BJT

Figure 2: Collpits Oscillators

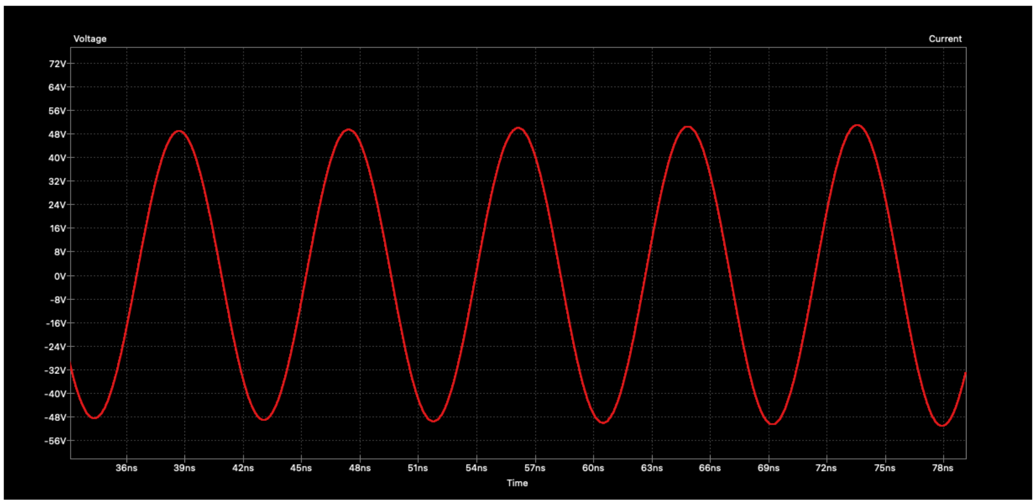


Figure 3: Differential Collpits Oscillator Simulation for Ideal NPN in NgSpice

1. The inductor and two capacitors form a resonant tank circuit. This circuit has a natural frequency at which it oscillates.
2. The feedback amplifier amplifies the alternating current (AC) signal from the tank circuit.
3. The feedback signal is fed back into the tank circuit, and the process repeats. This creates a positive feedback loop that sustains the oscillation.

The frequency of the Colpitts oscillator can be controlled by changing the values of the inductor and capacitors in the tank circuit. The frequency of oscillation is given by

$$f_0 = \frac{1}{2\pi\sqrt{L\dfrac{C_1C_2}{C_1+C_2}}} \tag{2}$$

However, single-ended Collpits has some issues as follows

1. Higher phase noise: Single-ended Colpitts oscillators tend to exhibit higher phase noise compared to differential oscillators. Phase noise is a measure of the randomness of an

oscillator's output, and it can degrade signal quality in applications where precise timing is critical.

2. Lower common-mode rejection: Single-ended Colpitts oscillators are susceptible to common-mode noise, which can interfere with the desired signal.

To address the limitations of single-ended Collpits oscillators, differential Collpits oscillators were developed using an extension of Collpits [**?**] and other configurations [**?**]. These oscillators employ two active devices connected in a balanced configuration, resulting in improved performance(Fig 2b). The two active devices generate a differential output signal, which is used to drive the resonant tank circuit and sustain the oscillation.

3.1.3 Antenna and Matching Network

We design the antenna and match it to the oscillator using a matching network(Fig 1). Matching networks, also known as impedance-matching circuits, are networks of passive components, such as inductors, capacitors, and transformers, that are used to match the impedance of a load to the impedance of a source. Impedance matching is an essential technique in RF engineering, as it can significantly improve the performance of RF systems. In RF systems, the impedance of the load and the impedance of the source must be matched to achieve maximum power transfer. If the impedances are not matched, there will be reflections of the signal, which will reduce the power transfer and lead to signal distortion.

The most straightforward matching-network topology is called the L network. This refers to eight different L-shaped circuits(Fig 4) composed of two capacitors, two inductors, or one capacitor and one inductor. The exact method for matching will be developed in the later phases of the project.

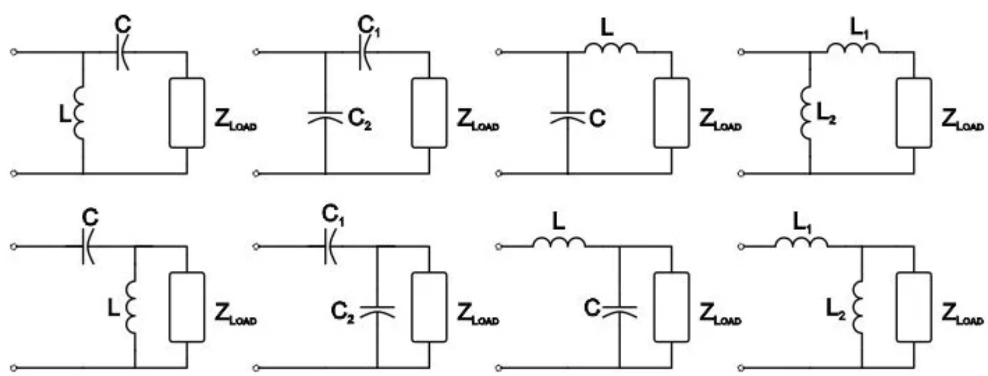


Figure 4: L-section Matching Networks

3.2 Project Requirements

The project requirements are as follows

1. The circuit will support an input range of 5-20[V]
2. The circuit will support frequencies up to 3.5[GHz]
3. The oscillating frequency must not differ by more than 100[MHz] from the required target frequency

4. The oscillator should function for a long time without decaying pulse

3.3 Required environment and tools

1. Designing Oscillator using Cadence PSpice:
   - Utilize Cadence PSpice for the design and simulation of the oscillator circuit.
   - Implement and validate the oscillator circuit in PSpice, considering real-world transistor characteristics.
   - Analyze simulation results to ensure stability, frequency accuracy, and harmonic content meet project requirements.
2. Testing S-Parameters and Matching using Cadence Virtuoso:
   - Employ Cadence Virtuoso for testing S-parameters and optimizing the matching network.
   - Simulate the matching network design to achieve a $50[\Omega]$ impedance match for the antenna.
   - Analyze S-parameters, including return loss and insertion loss, to validate the effectiveness of the matching network.
3. Testing the Antenna using EMF Simulation using CTS/MATLAB:
   - Use CTS (Circuit Telecommunication Simulation) and MATLAB for electromagnetic field (EMF) simulation of the antenna system.
   - Simulate the antenna's radiation characteristics, efficiency, and impedance matching in realistic environmental conditions.
   - Analyze simulation results to ensure the antenna meets specified requirements and integrates seamlessly with the overall transmitter system.

4 Project Deliverables

To achieve the project objectives, the following detailed deliverables have been outlined:

1. Working Spice Model of Chosen Transistor:
   - Develop and validate a detailed Spice model for the selected transistor.
   - Conduct simulations to demonstrate the transistor's functionality and performance characteristics.
   - Include results such as voltage-current characteristics, frequency response, and transient analysis.
2. Oscillator Design and Simulation:
   - Design an oscillator circuit capable of generating the required frequency.
   - Simulate the oscillator performance using both ideal and real transistor models.
   - Present simulation results in time domain, FFT analysis, and S-parameters in Virtuoso.
   - Include detailed analyses of stability, frequency accuracy, and harmonic content.
3. Matching Network Design and S-Parameters Analysis:
   - Design a matching network to achieve a $50[\Omega]$ impedance match for the antenna.
   - Simulate the matching network and present S-parameters to validate the impedance matching.
4. Antenna System Implementation:
   - Develop and simulate the antenna system to be integrated into the transmitter.
   - Include simulation results demonstrating antenna efficiency, radiation patterns, and impedance characteristics.
5. Transmitter Simulation and PCB Layout:
   - Simulate the entire transmitter system, incorporating the oscillator, matching network, and antenna.
   - Utilize an EMF simulator to assess electromagnetic compatibility and ensure proper functioning.
   - Create a detailed PCB layout considering optimal component placement for signal integrity.
   - Conduct simulations to validate the PCB layout's impact on signal quality and interference.
6. PCB Fabrication and System Testing:
   - Fabricate the PCB according to the finalized layout.
   - Conduct testing using a pre-built receiver to validate the overall system performance.
   - Include test results such as signal strength, frequency accuracy, and reliability.
   - Document any issues encountered during testing and propose potential solutions.

5 Project Schedule

	Milestones	Description	Date
1	Paper review	Conduct a thorough review of relevant literature and research papers to establish a foundation for the project.	15/1
2	Choosing an oscillator model to build upon	Evaluate and select a suitable oscillator model as the basis for further development. Consider factors such as stability and frequency range.	21/1
3	Building Ideal Single-Ended Oscillator Model and Simulating for S-parameters	Construct an ideal single-ended oscillator model and perform simulations to analyze S-parameters, ensuring initial functionality.	21/2
4	Building the Differential counterpart and Simulating for S-parameters	Extend the oscillator model to a differential configuration, simulating and analyzing S-parameters for enhanced performance.	28/2
5	Choosing transistor, building its spice model and using it in place of ideal one	Identify a suitable transistor, develop its Spice model, and integrate it into the oscillator model, replacing the idealized component.	14/3
6	**Progress Presentation Submission**		
7	Reserach on Antenna matching	Reading papers related to antenna matching for design inspirations	21/3
8	Building a matching assuming antenna to be 50[Ω]	Design a matching network under the assumption of a 50[Ω] antenna impedance. Simulate and optimize for effective impedance matching.	14/4
9	Using Antenna with required impedance	Develop an antenna system with the specified impedance characteristics, considering radiation patterns and efficiency.	14/5
10	**Poster Submission and finishing the work**		
11	PCB layout	Design the printed circuit board (PCB) layout, considering optimal component placement	1/6
12	PCB fabrication	Fabricating the design	1/8
13	Testing Transmitter	Conduct comprehensive testing of the assembled transmitter system to validate its functionality and performance.	7/8
14	**Final deliverables submission**		