University of Pennsylvania

School of Engineering and Applied Science

Department of Electrical and Systems Engineering

ESE 3190 — Spring 2025

Fundamentals of Solid-State Circuits

PreLAB 10 | Final Project

Metal Detector

Hesham Nabil Hosny Maher 58309713

Submission Date: Friday, April 18, 2025

Introduction

The goal of this project is to design and verify an analog metal detector circuit that produces an audible tone when metallic objects are detected. The system leverages changes in inductance due to the presence of nearby metal, which causes a shift in oscillator frequency. The circuit architecture includes two LC oscillators: one with a fixed inductor and the other with a variable inductor placed near a potential metal object. When the variable inductor is exposed to a metallic object, its inductance increases, reducing its oscillation frequency.

The outputs of both oscillators are fed into a differential amplifier (mixer), which generates both the sum and difference of the input frequencies. This produces a beat frequency equal to the difference between the two oscillators. A nonlinear common-source amplifier is used to enhance the low-frequency components. A low-pass filter isolates the beat signal, and a power stage drives an 8-ohm speaker to generate an audible output. This report documents the simulation of each stage and validates the expected signal behavior, including a beat frequency of approximately 1 kHz.

Theory and Operation

Oscillator Design

The circuit includes two cross-coupled LC oscillators. Each oscillator uses a parallel inductor-capacitor tank and a cross-coupled NMOS/PMOS pair to create sustained oscillations. The frequency of oscillation is determined by the resonance of the LC tank:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

In this design:

- The **fixed oscillator** uses $L_1 = 10\,\text{mH}$, $C_1 = 1013\,\text{pF} \rightarrow f \approx 50\,\text{kHz}$

- The **variable oscillator** uses $L_2 = 9.17\,\text{mH}$, $C_2 = 1150\,\text{pF} \rightarrow f \approx 49\,\text{kHz}$

A nearby metal object alters the inductance of L_2, causing a measurable frequency shift in the variable oscillator.

Mixer Stage

The two oscillator outputs are fed into a differential amplifier built from NMOS transistors (M11–M14), biased using a current source. The mixer outputs both the sum and difference frequencies:

$$f_{\text{sum}} = f_1 + f_2, \quad f_{\text{diff}} = |f_1 - f_2|$$

For normal conditions, $f_{\text{diff}} = 1\,\text{kHz}$. The output at this stage is amplitude-modulated and contains high-frequency components.

Common-Source Amplifier

The mixer output feeds into a common-source (CS) amplifier (M15) with resistive load. The CS amp introduces nonlinearity, which enhances the low-frequency beat tone. It also increases the signal amplitude before filtering. This stage is biased using a voltage divider to ensure operation in the saturation region.

Low-Pass Filter

To isolate the 1 kHz beat tone, a second-order low-pass filter follows the CS amp. The filter is made up of two capacitors (100 nF, 200 nF) and three resistors, forming an RC ladder network. It suppresses the high-frequency content from the mixer while preserving the audible beat tone.

Output Stage

The filtered signal controls the gate of a PMOS-NMOS buffer stage. The final output transistor (M17, IRL8721PBF) drives an 8Ω resistive load simulating a speaker. The presence of a 1 kHz signal at this node confirms proper metal detection and signal flow through all stages.

Simulation Setup

All simulations were performed in LTspice using a 6V supply. The speaker was modeled as an 8Ω resistor. Simulations were run for 10 ms.

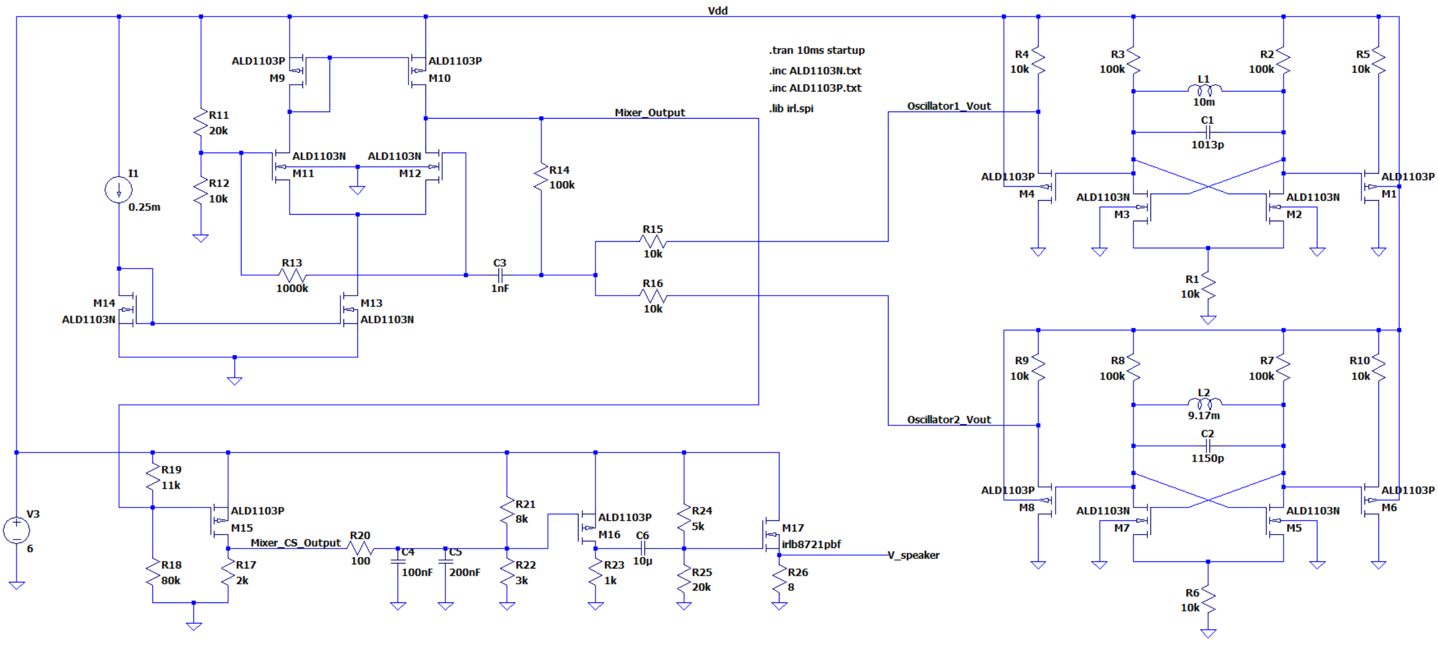

Figure 1: LTspice schematic showing oscillator, mixer, amplifier, and output stages.

Oscillator Outputs with no increase

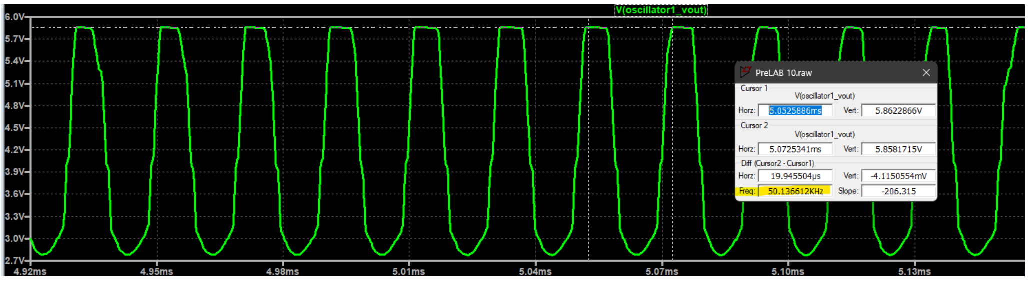

Figure 2: Oscillator1 (Fixed) output. Frequency: 50 kHz.

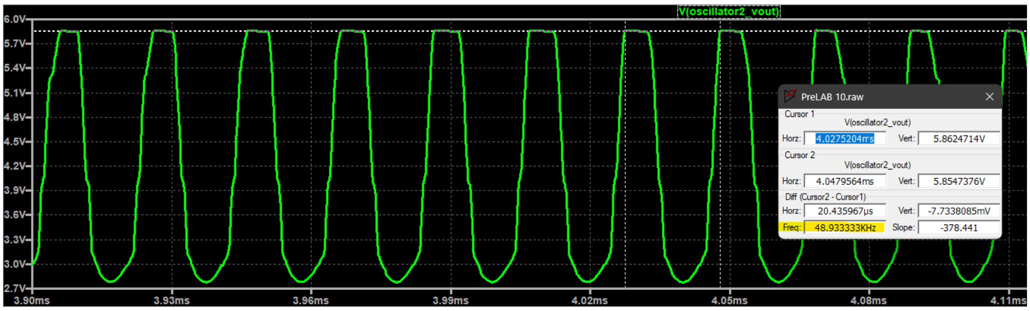

Figure 3: Oscillator2 (Variable) output. Frequency: 49 kHz.

Oscillator Outputs with 5% inductance increase

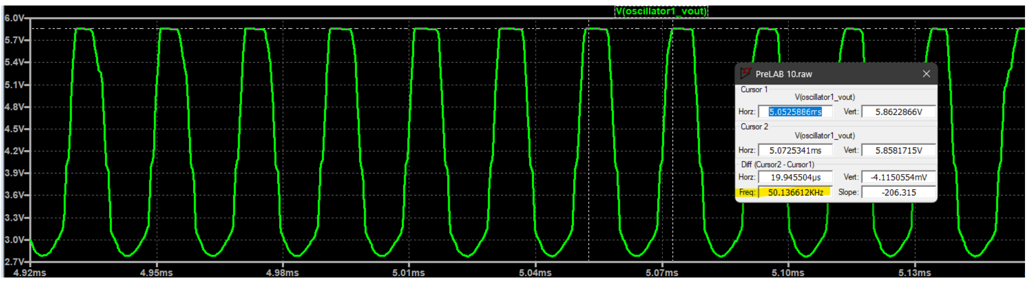

Figure 4: Oscillator1 (Fixed) output. Frequency: 50 kHz.

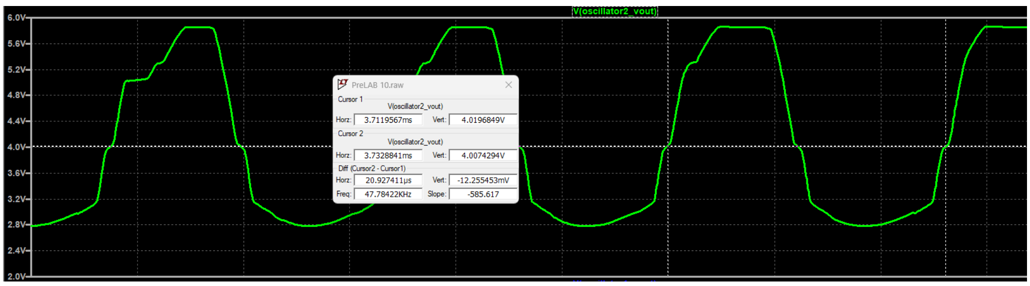

Figure 5: Oscillator2 (Variable) output. Frequency: 47.6 kHz.

Mixer Output With no increase:

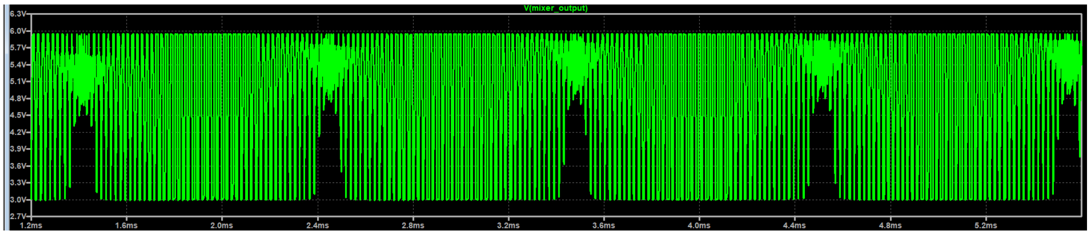

Figure 6: Mixer output under normal conditions.

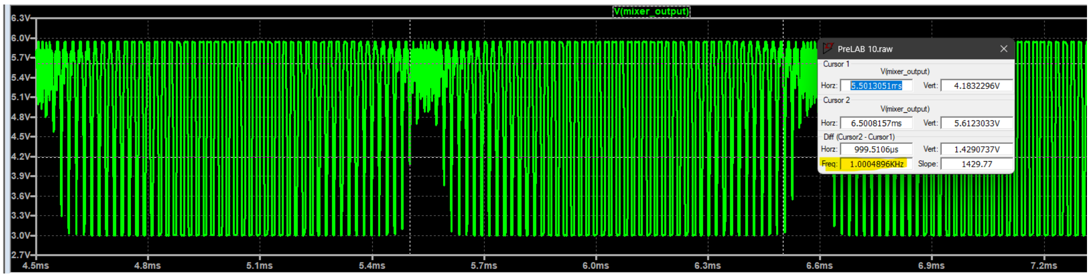

Figure 7: Mixer output under normal conditions.Beat frequency: 1 kHz.

Mixer Output With 5% inductance increase:

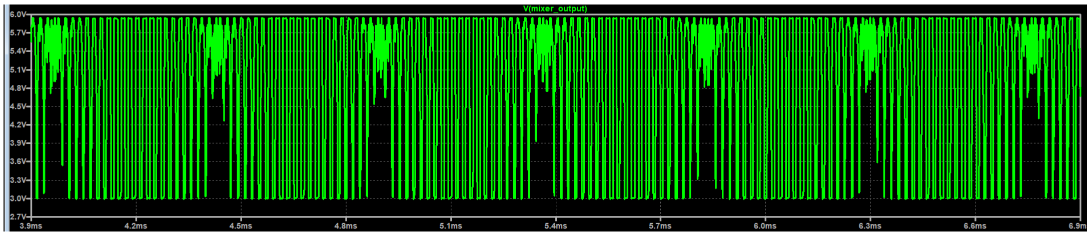

Figure 8: Mixer output with metal nearby. Beat frequency increases.

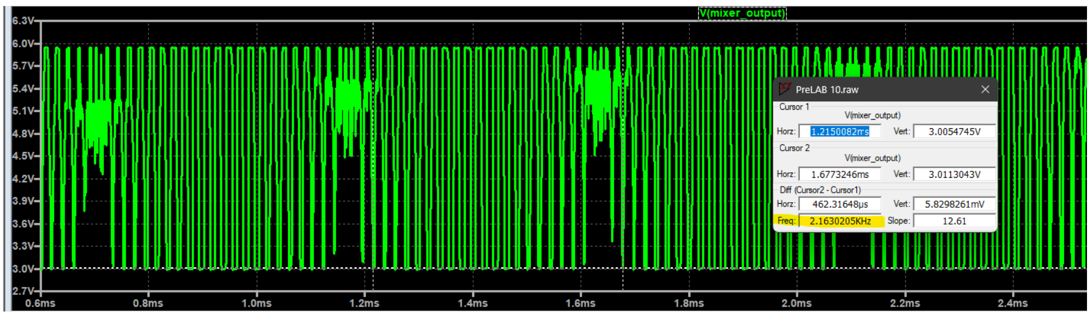

Figure 9: Mixer output with metal nearby. Beat frequency: 2.2 KHz.

Final Output (Speaker Voltage):

Speaker Voltage before any increase in the inductance :

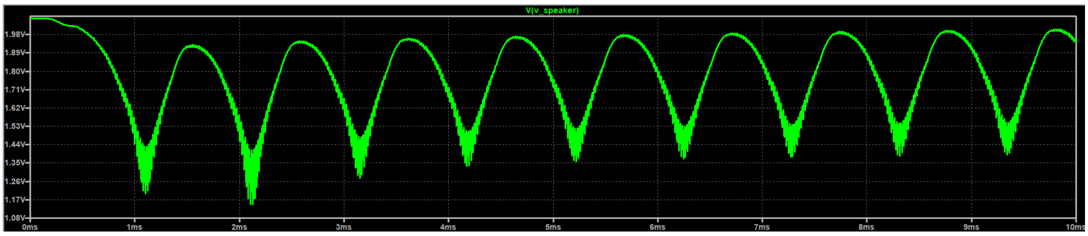

Figure 10: Voltage across 8Ω resistor simulating the speaker. 1 kHz signal.

Speaker Voltage before after 5% increase in the inductance :

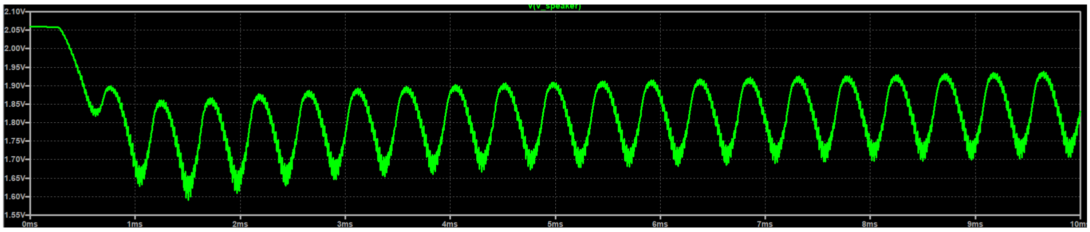

Figure 11: Voltage across 8Ω resistor simulating the speaker. 2.3 kHz signal.

Checkpoint Questions

1. **Oscillator frequency equation:**

$$f = \frac{1}{2\pi\sqrt{LC}}$$

2. **What issues might arise if the oscillator frequency is 5kHz or 500kHz?** At lower frequencies, the output would lack clarity due to a broad, indistinct envelope. At higher frequencies, circuit limitations could cause instability or failure, especially around the nonlinear stages.

3. **What is the purpose of making Vb tunable?** It allows manual adjustment to correct for variation in circuit components, ensuring consistent performance even when part tolerances differ.

4. **What is the fundamental frequency played by the speaker?** The speaker outputs a 1 kHz tone, which corresponds to the difference between the two oscillator frequencies under normal conditions.

5. **How does changing Rvar impact the mixer current?** Rvar influences the voltage at the tail of the differential pair, which sets the operating point and controls how much current flows through the mixer.

6. **Why can't Vcs connect directly to the speaker?** The signal at Vcs includes multiple frequency components. To isolate the beat frequency and reject higher-frequency content, it must first pass through a low-pass filter before reaching the output stage.

7. **What happens if another capacitor is added to the low-pass filter?** Adding a capacitor lowers the cutoff frequency, which enhances attenuation of higher-frequency noise and makes the output signal cleaner.

8. **What happens if R in the CS amp is increased?** A higher resistor value boosts the amplifier's gain but also raises the output voltage level and may shift the transistor's bias point.