ABSTRACT

Title: Implementation of a Nonlinear Square Root Computational Circuit in eSim using Op-Amp and 180nm Technology Library

Theory/Description: The **Square Root Amplifier** is a specialized nonlinear analog computational circuit designed to produce an output voltage proportional to the square root of the input voltage. This is achieved by exploiting the inherent physical characteristics of semiconductor devices—specifically the **MOSFET**—placed within the feedback loop of an operational amplifier.

Explanation:

- **Input Current Generation (I_in):** The input voltage is applied to resistor R1 (100kohm). Because the non-inverting terminal (Pin 3) of the LM741 is grounded, the inverting terminal (Pin 2) acts as a **virtual ground**. This creates an input current:

  I_in = V_in/R1

- **Feedback Balancing:** According to Kirchhoff's Current Law (KCL), the current entering the inverting terminal must exit through the feedback path (since the Op-Amp's input impedance is ideally infinite). In my circuit, this feedback path contains the **NMOS (MN1)**. Therefore,I_in=I_D (the drain current of the MOSFET).
- **The Square-Law Constraint:** The NMOS is connected such that its Gate is tied to the Op-Amp output and its Source is at the virtual ground. This makes equal to the Op-Amp's output

voltage. When in the saturation region, the MOSFET forces the current to follow a squared relationship:

I_D is proportional to (V_{GS} -V_{th})^2

- **Mathematical Extraction of the Root:** Since the Op-Amp must keep $I_{in}=I_D$, it automatically adjusts its output (V_{out}) to satisfy the equation:

$$V_{in}/R1 = K(V_{out} - V_{th})^2$$

To balance this, must physically become the **square root** of the input voltage to maintain the equality.

- **Signal Inversion and Offset:** Because this is an inverting configuration, the output moves in the opposite direction of the input. Additionally, as you noticed in your plots, the output is "pre-biased" by the **Threshold Voltage (Vth)**. Even at low V_{in}, the Op-Amp must output approximately just to turn the MOSFET on so that feedback can begin.
- **High-Frequency Stability(during transient analysis):** The 10pF **capacitor (C1)**added in parallel with the MOSFET provides a low-impedance path for high-frequency noise. This prevents the nonlinear feedback loop from becoming unstable or oscillating during the transient transitions you saw in your sine wave simulation.
- **The Compression Result(during transient analysis):** As shown in transient graph, as V_{in} increases, the I_{in} increases linearly, but because of the square-root nature of the feedback,V_{out} only needs to change by a very small amount to accommodate that extra current. This is why 3V input swing resulted in a tiny ~42mV output swing.

DC Analysis:

Parameters:

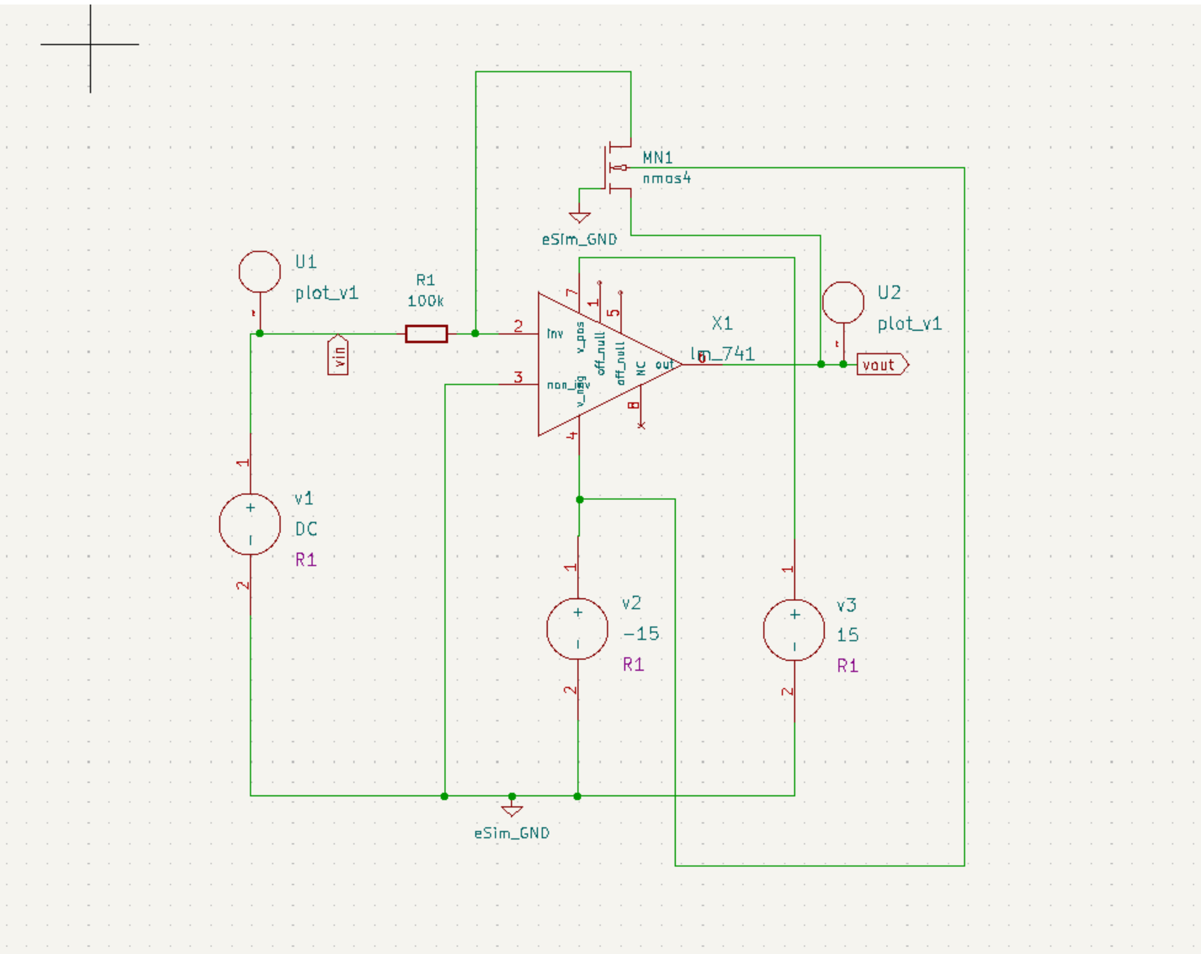
Source : V1

Start: 0.4 V

Step : 0.1V

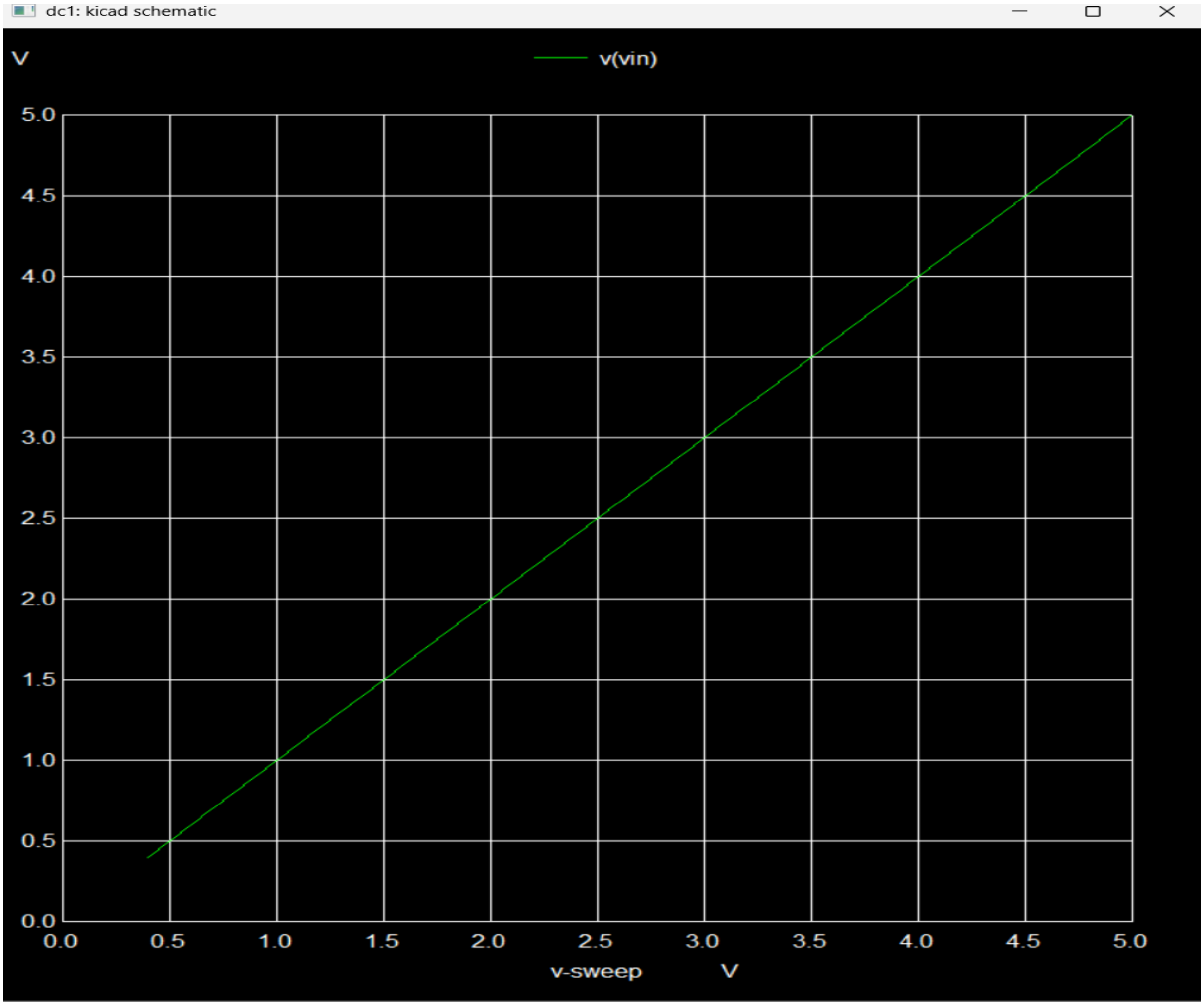
Stop: 5V

Circuit Diagram:



Results/Output(ngspice plots):

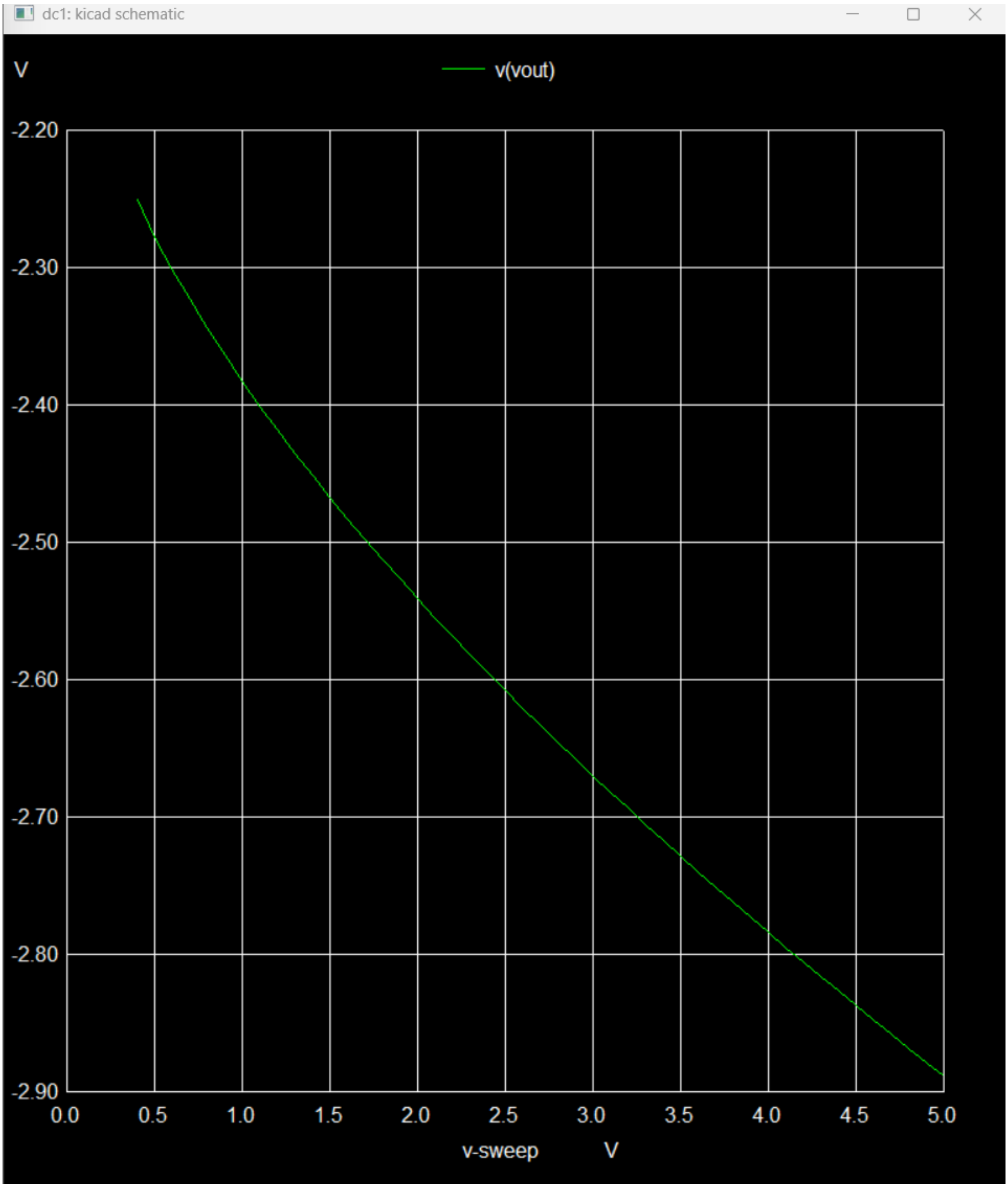
Input:



Output:

The **X-axis** of output plot represents the input voltage sweep 0V to 5V and the **Y-axis** shows the compressed square-root response.

Starting from **0.4V** ensures the MOSFET operates in a stable, predictable region. At **0V**, the input current is zero, causing the op-amp to hit the positive rail or lose feedback control. Beginning at a non-zero value avoids this "dead zone," ensuring the transistor is biased for immediate conduction.



AC Analysis:

Parameters:

Start time: 0 sec

Step time: 1microsec

Stop time: 5msec

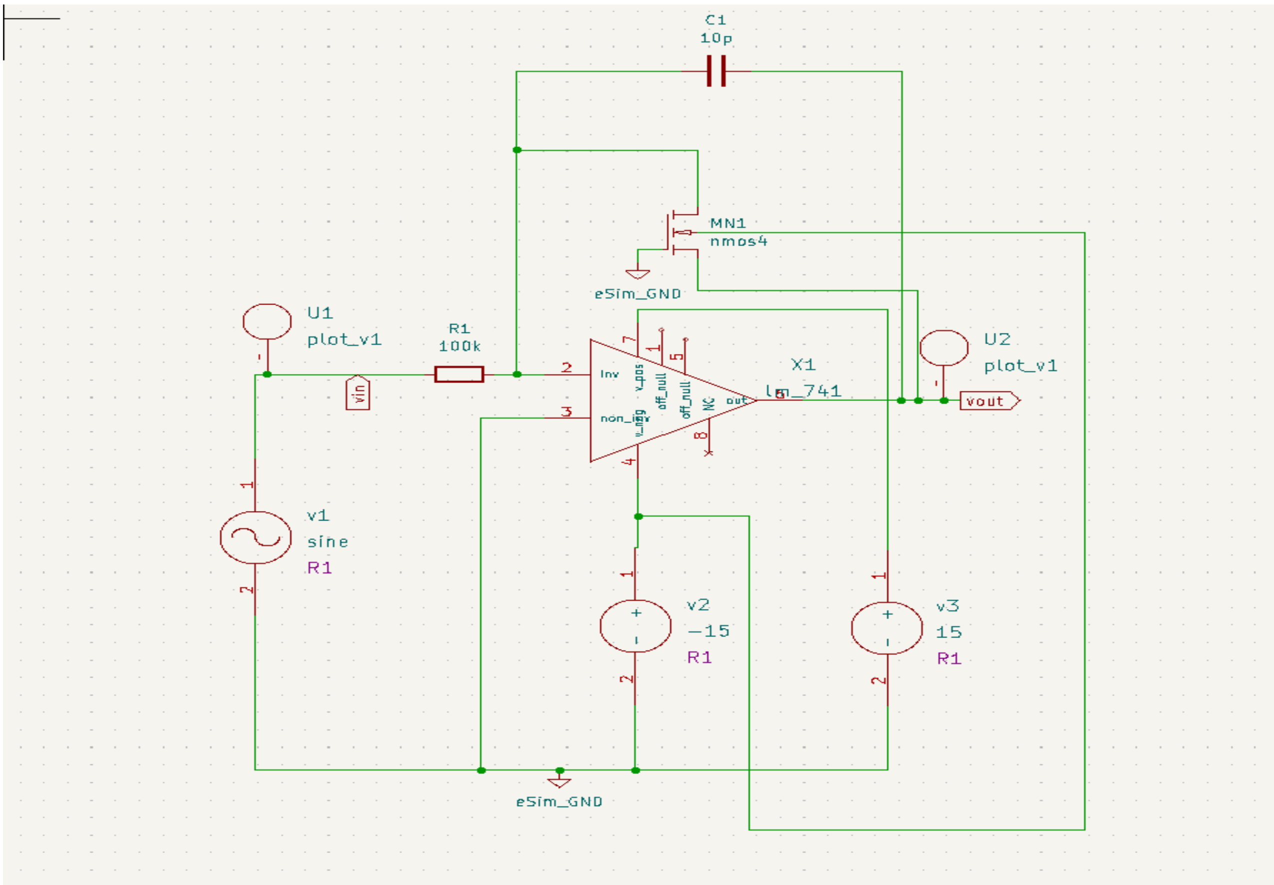
Sine source: V1

Offset value:2.5V

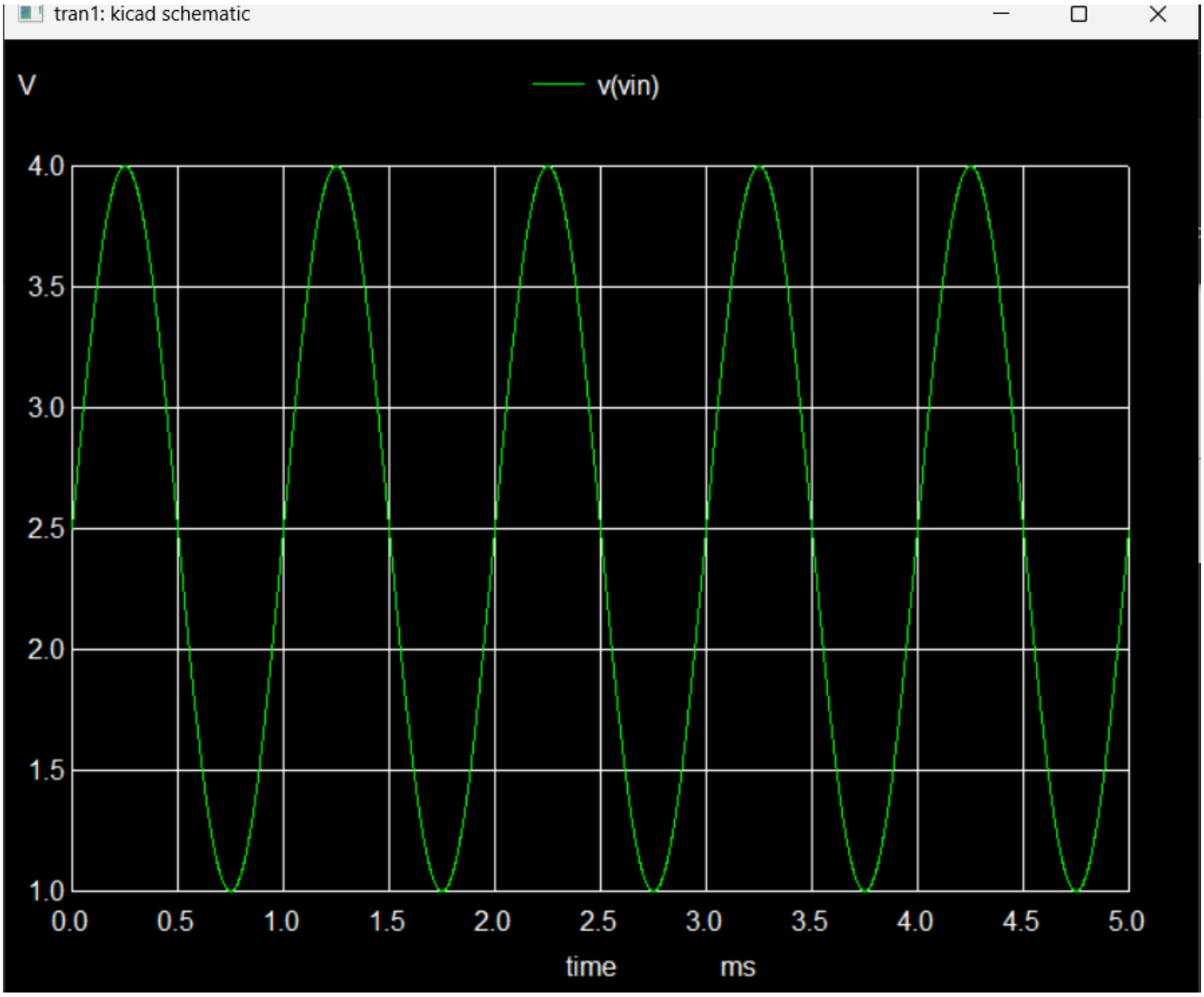
Amplitude: 1.5V

Frequency: 1kHz

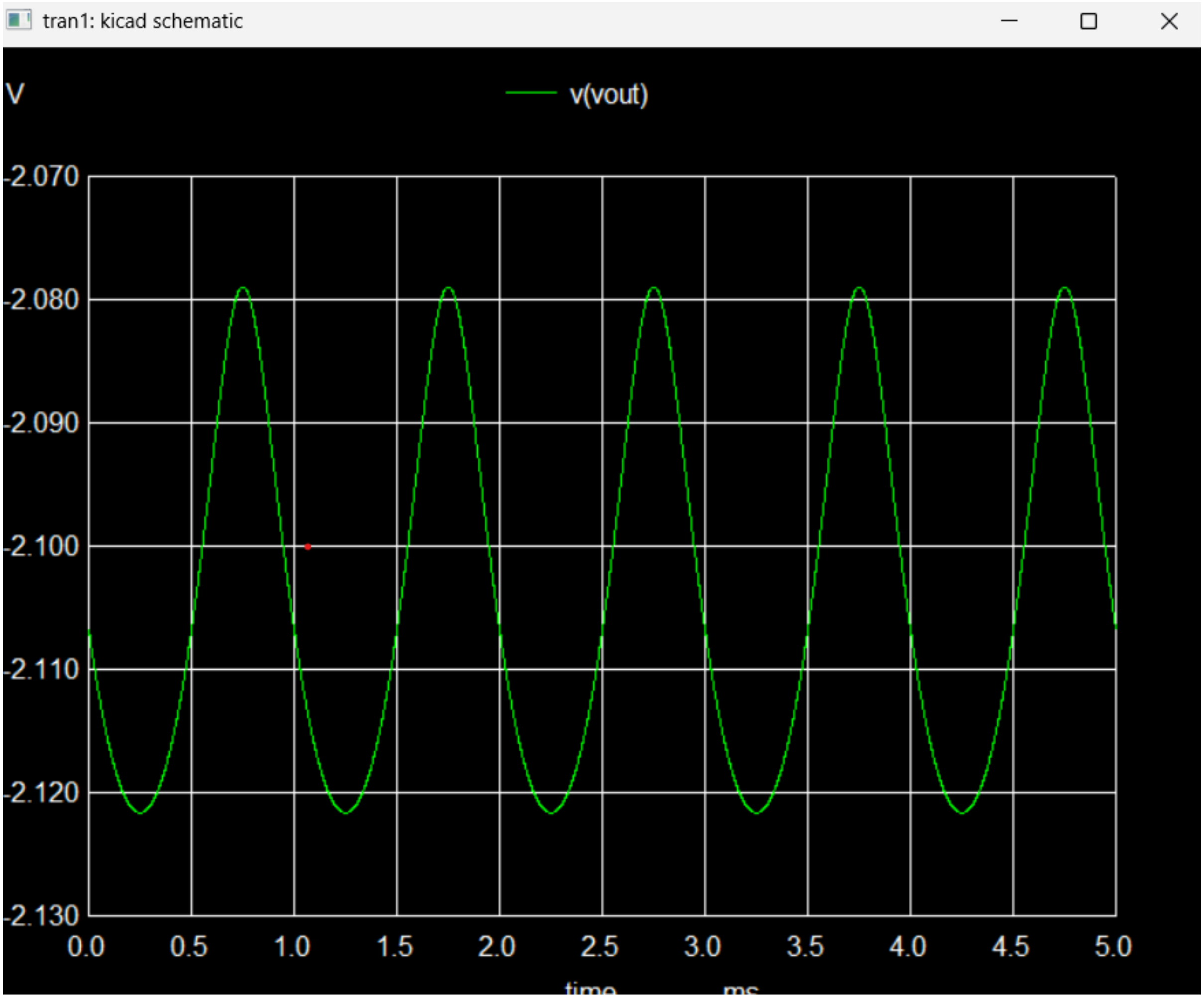
Circuit Diagram:



Input:


tran1: kicad schematic
V
v(vin)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
time
ms

Output:



The transient analysis demonstrates the compressive nature of the nonlinear square root amplifier. A large 3V swing at the input is compressed into a small ~42 mV swing at the output, centered around the MOSFET's threshold voltage (V_th = 2.1 V).

Application: this circuit is a "Computational Building Block" used in analog signal processing to linearize sensors that have a squared output characteristic.

References:

Links:

Title of the paper: A Simple Square Rooting Circuit Based on Operational Amplifiers (OPAMPs).

Link:
https://www.researchgate.net/publication/346751971_A_Simple_Square_Rooting_Circuit_Based_on_Operational_Amplifiers_OPAMPs

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