Design and Simulation of Single-Balanced and Double-Balanced Passive MOSFET Mixers

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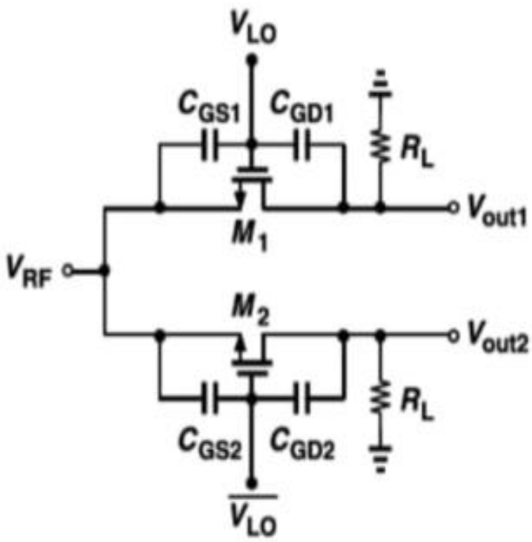
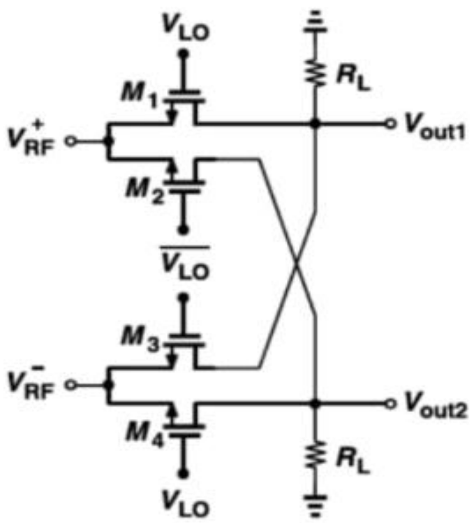
Theory and Description:

Frequency mixers are critical components in radio frequency (RF) front-ends, responsible for frequency translation via the multiplication of a Radio Frequency (RF) signal and a Local Oscillator (LO) clock. Passive mixers are widely preferred in modern CMOS integrated circuits due to their zero DC power consumption, excellent linearity, and low flicker (1/f) noise compared to their active counterparts.

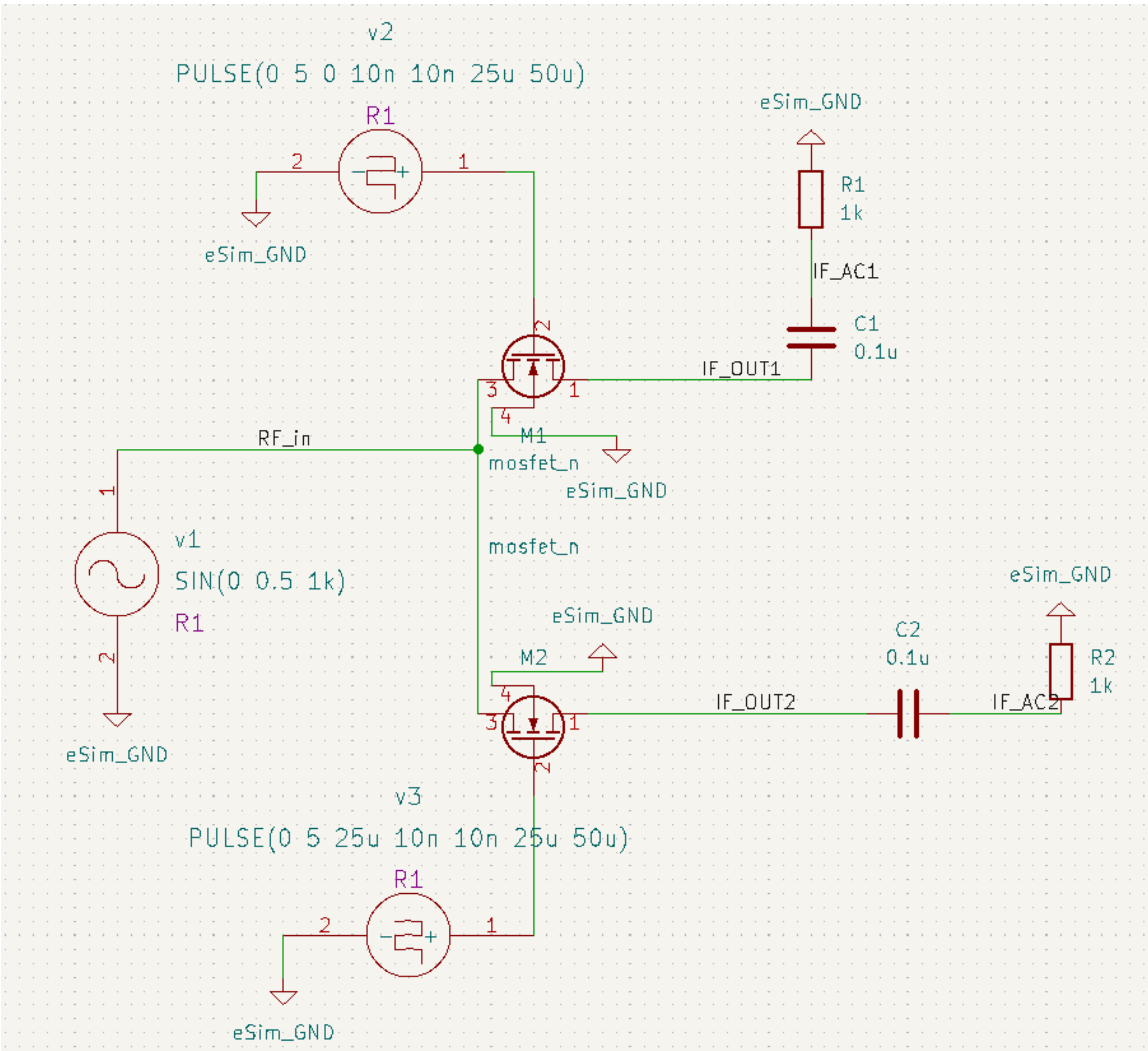
However, standard single-balanced passive mixers suffer from severe LO-to-IF feedthrough. Because the LO signal drives the gates of the mixing transistors, strong switching transients couple directly into the intermediate frequency (IF) output port, necessitating high-order, off-chip filtering. By utilizing a cross-coupled bridge topology consisting of four NMOS switches driven by differential RF and LO signals, the architecture provides inherent port-to-port isolation. The symmetrical nature of the ring ensures that the positive and negative LO clock signals destructively interfere at the output nodes, mathematically cancelling the common-mode LO leakage and achieving near-perfect carrier suppression entirely at the hardware level.

Circuit Diagrams:



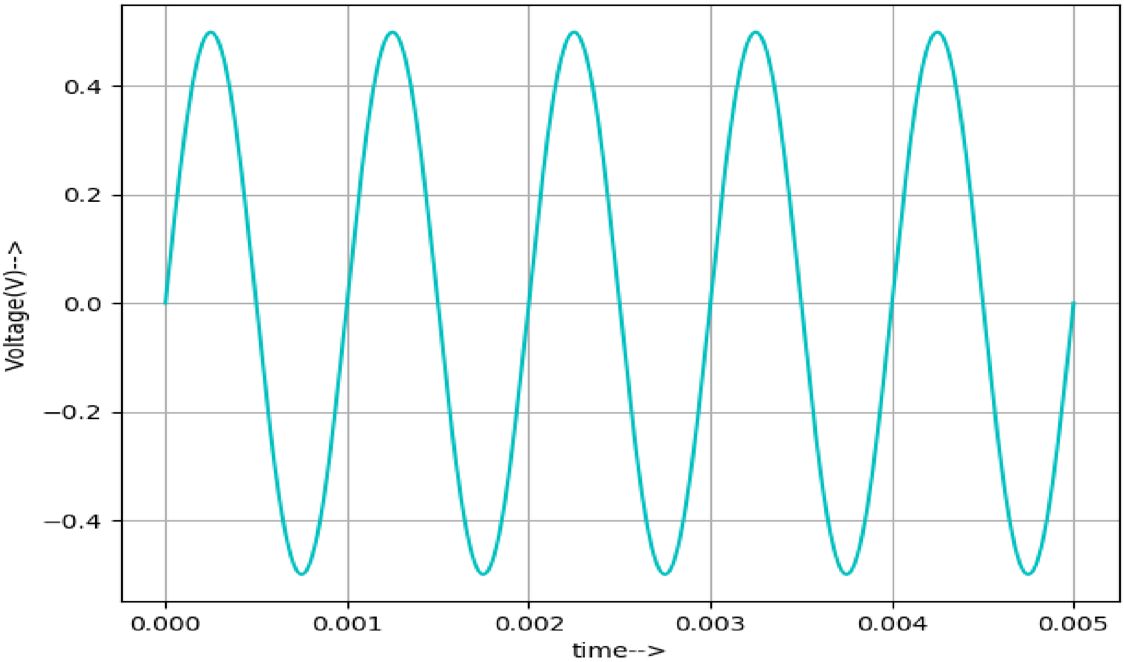


Ki-cad Schematic:

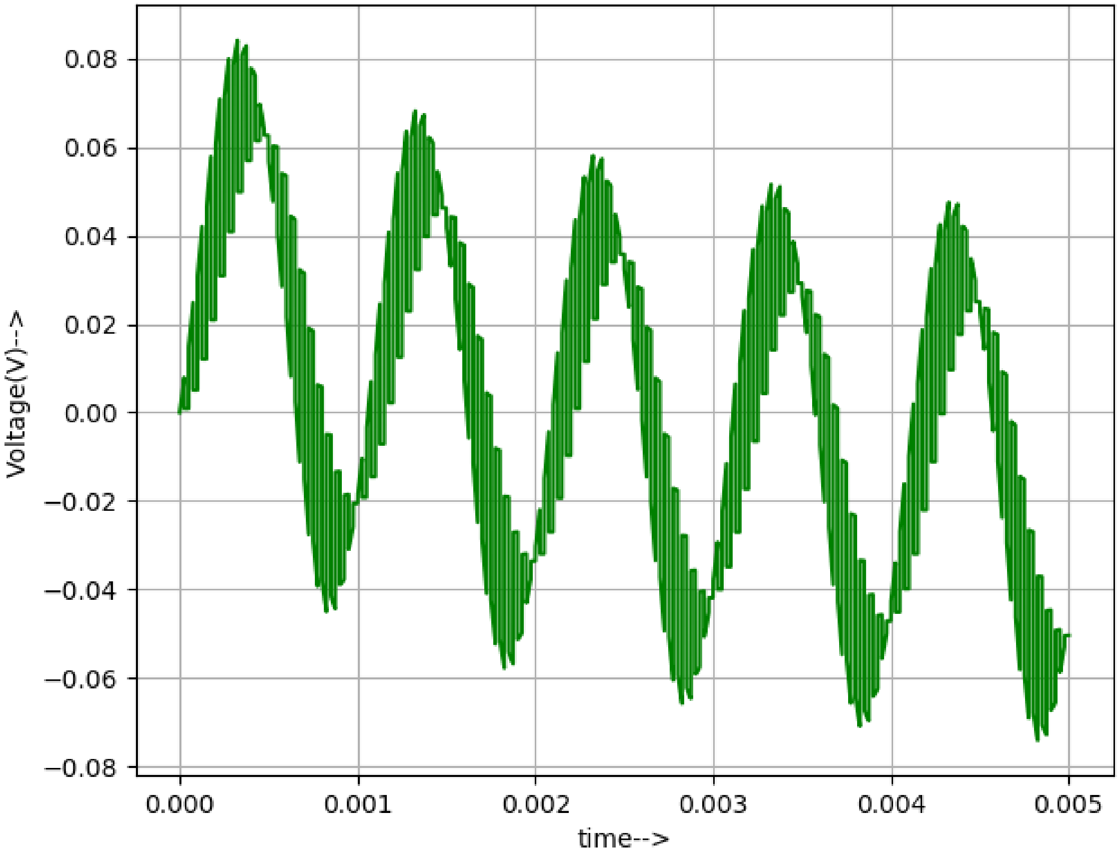


Single-Balanced Passive Mixer

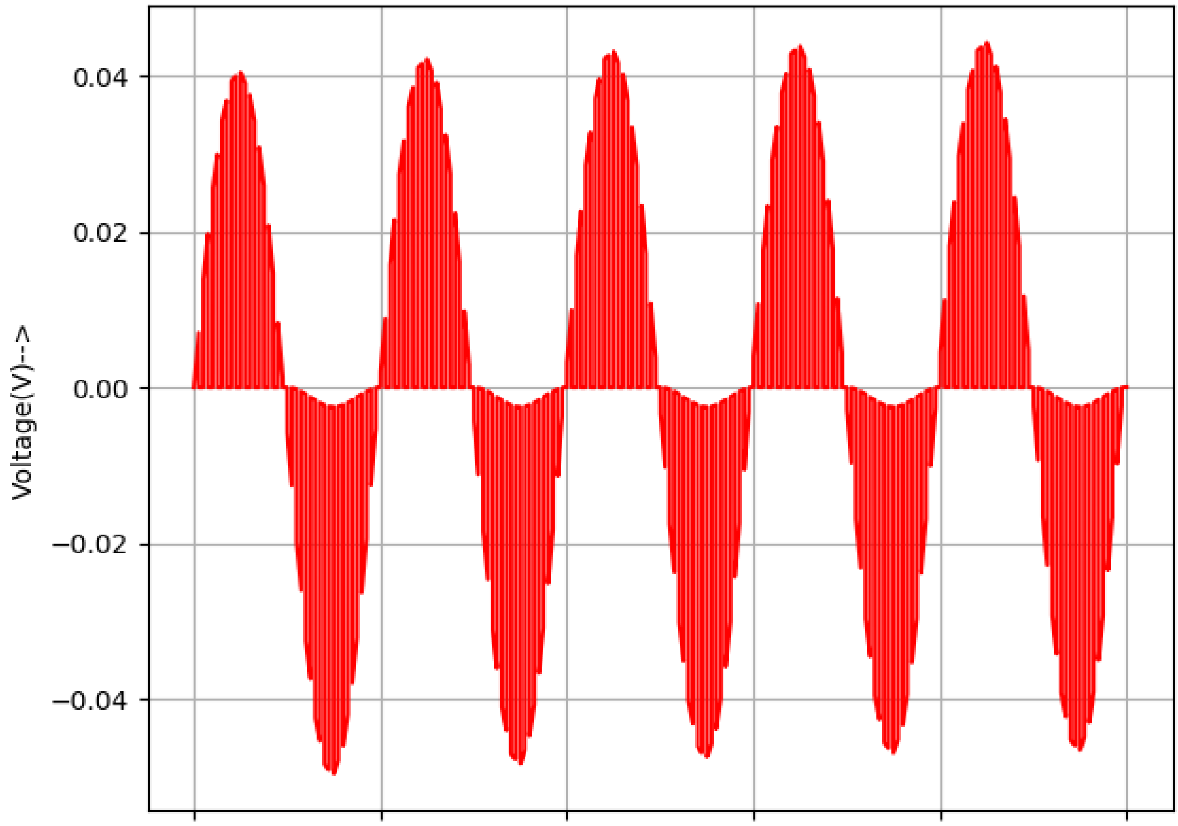
Outputs:



Transient Analysis of 1 kHz RF Input Signal



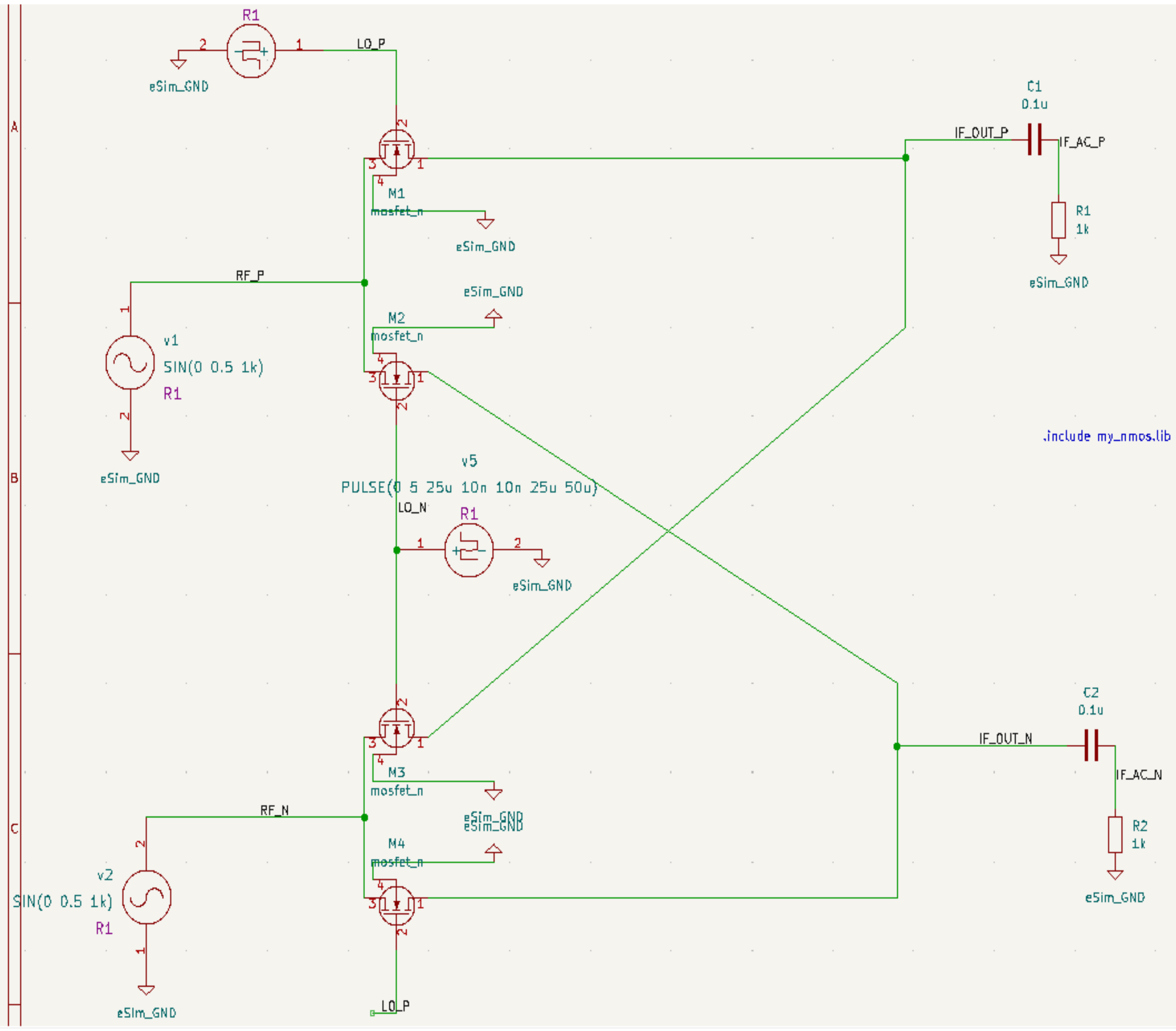
Transient Analysis of Raw DC-Coupled IF Output (Node: /if_out1)



Transient Analysis of AC-Coupled IF Output (Node: /if_ac1)

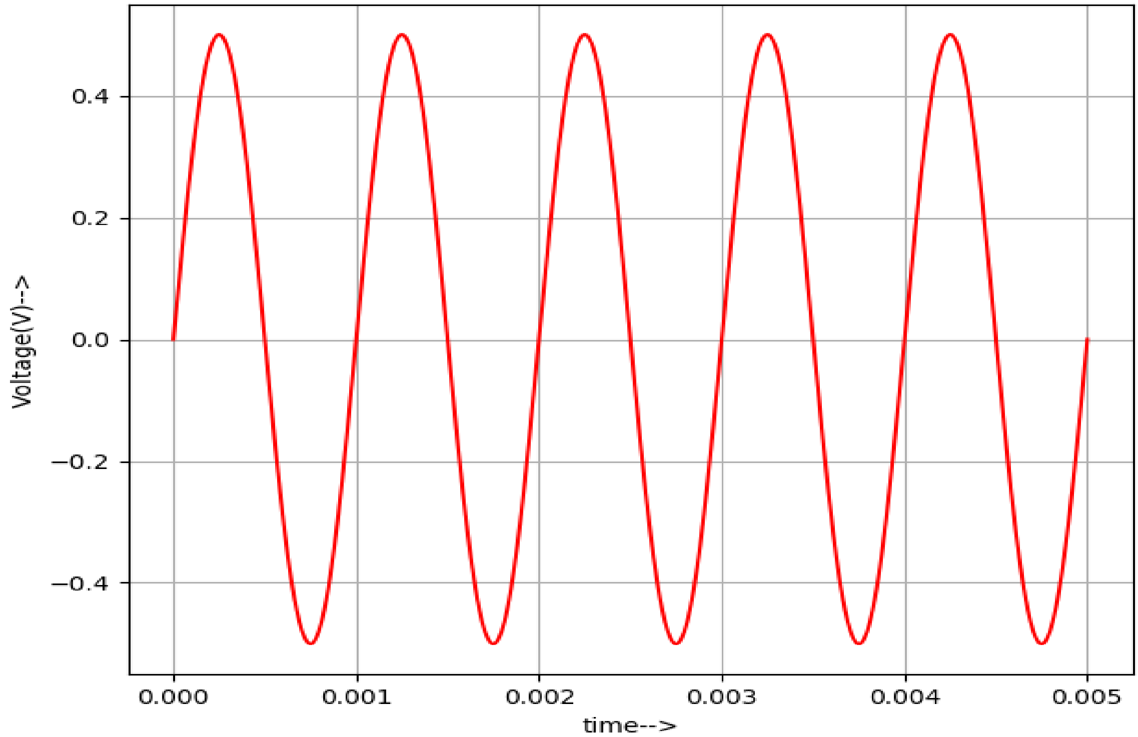
While the single-balanced mixer successfully achieves basic frequency translation, it presents a critical structural flaw for modern RF integration: severe Local Oscillator (LO) feedthrough. Because the single-balanced topology only balances one of the input ports, the high-amplitude LO clock signal leaks directly into the Intermediate Frequency (IF) output. In a physical application, removing this massive unwanted carrier spike would require complex, high-order off-chip filters, significantly increasing the cost, power, and physical footprint of the system. To overcome this limitation, the project was deliberately expanded to design and simulate a fully double-balanced ring topology. By utilizing a cross-coupled four-transistor bridge, the double-balanced architecture inherently suppresses this LO leakage entirely in the hardware. This transition demonstrates a clear progression in solving critical signal integrity challenges, achieving superior port-to-port isolation and maximizing conversion gain without the need for expensive output filtering.

Ki-cad Schematic:

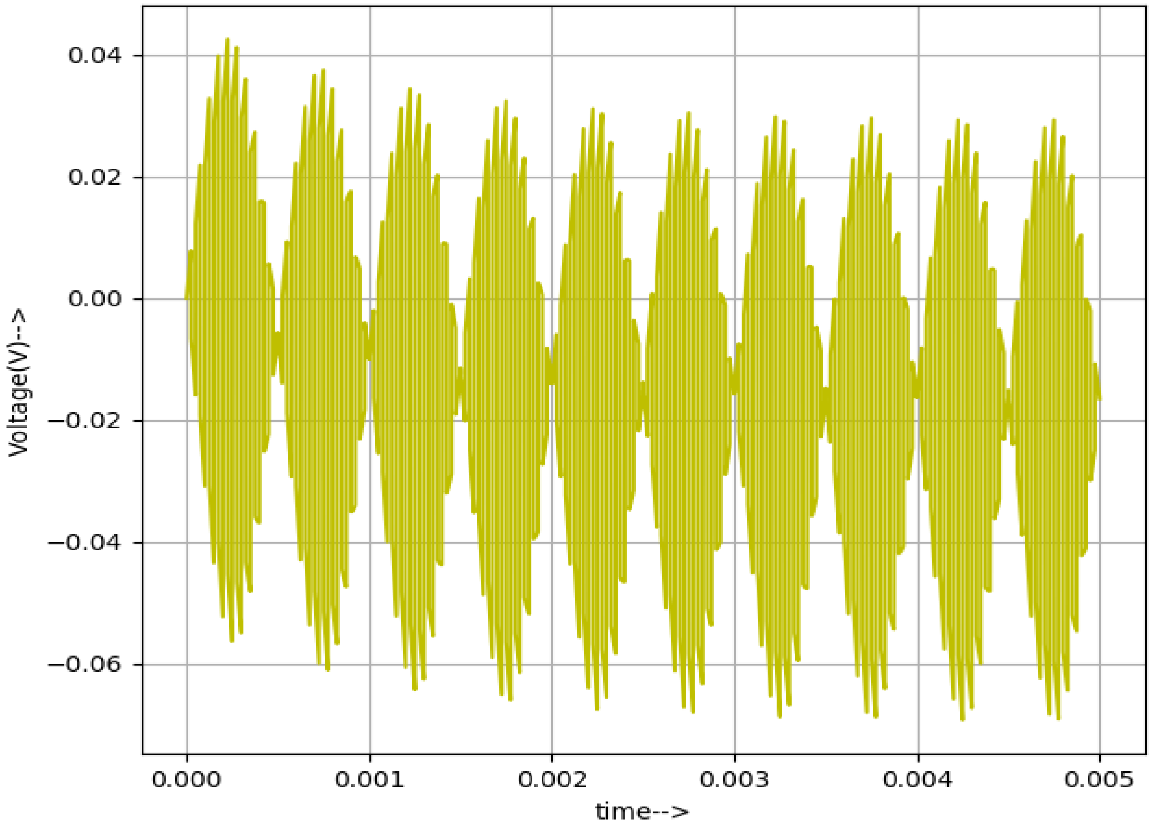


Double-Balanced Passive Mixer

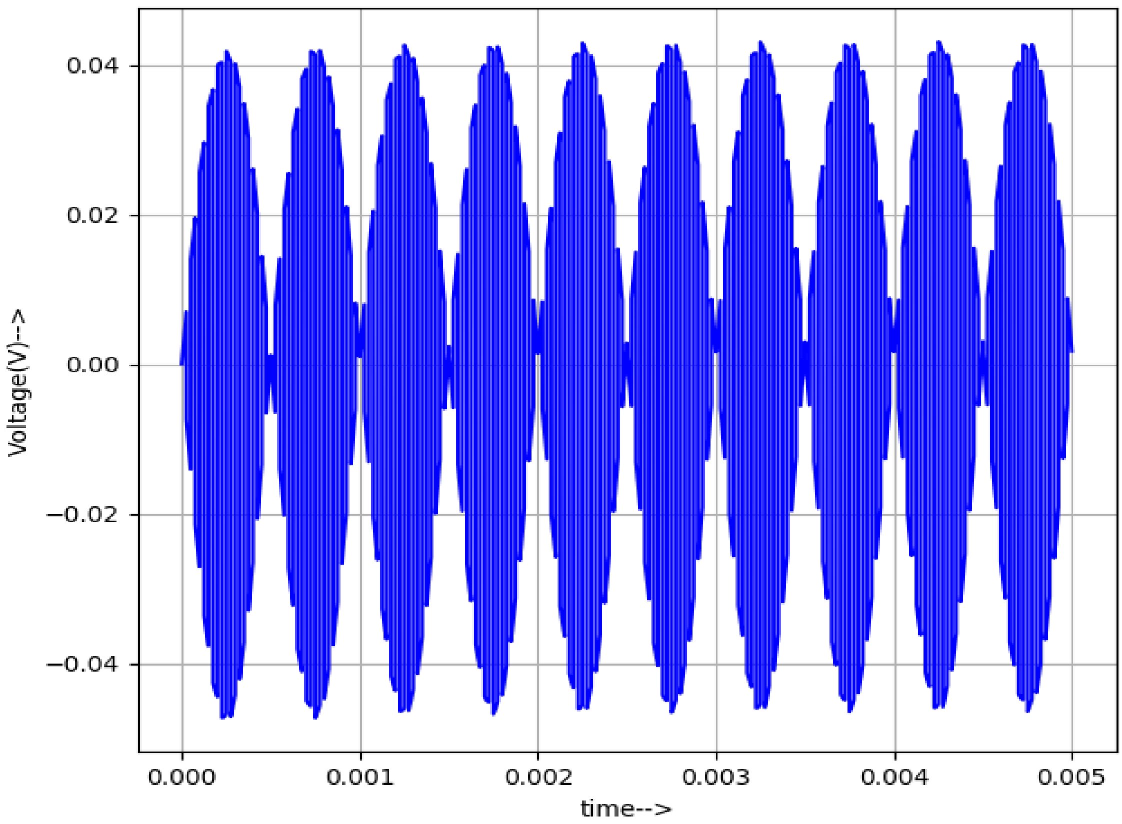
Outputs:

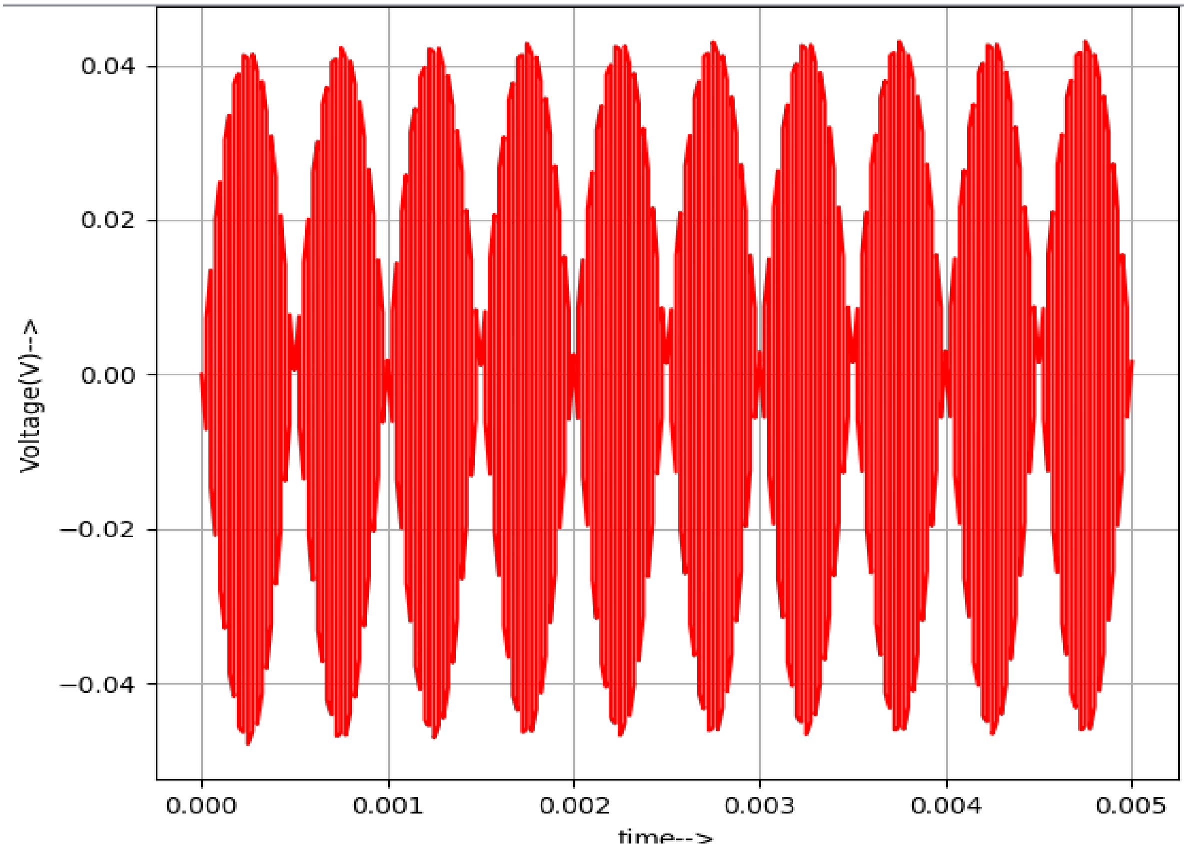


Transient Analysis of Positive RF Input Signal (Node: /rf_p)



Transient Analysis of Raw DC-Coupled IF Output (Node: /if_out_p)



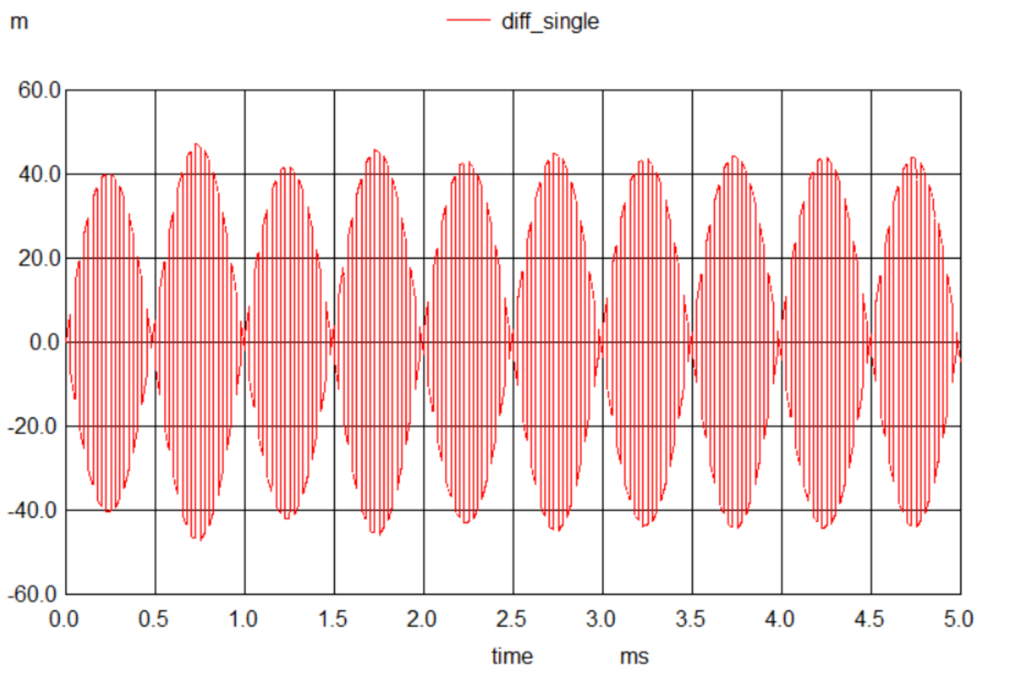


Transient Analysis of AC-Coupled IF Outputs

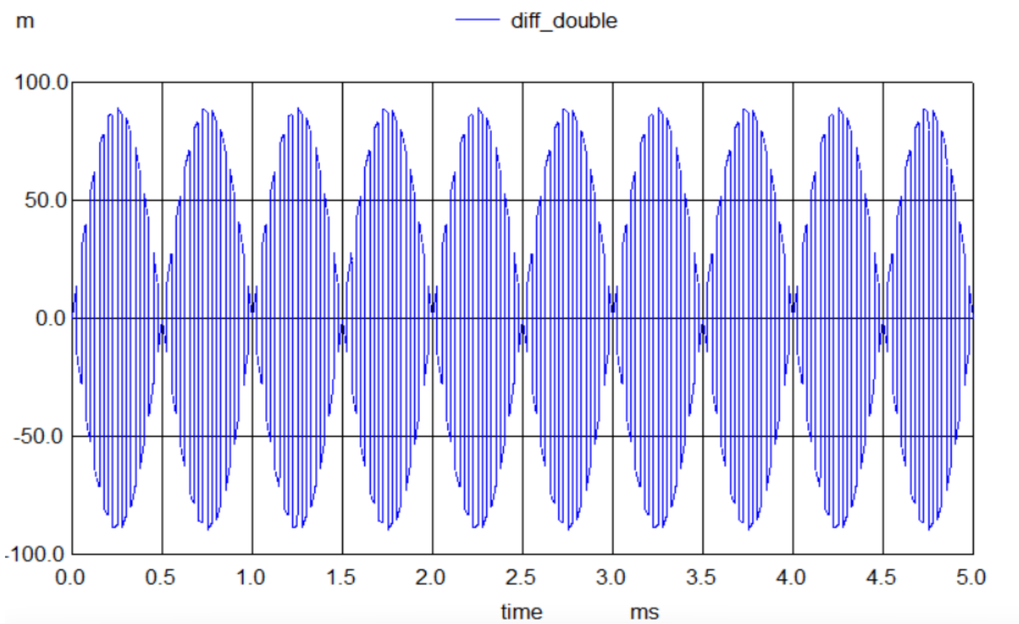
Comparative Analysis (Differential Outputs)

To evaluate the true performance of both topologies, the differential AC-coupled signals were extracted and compared. This represents the final IF output after DC offset removal and differential subtraction.

Differential Time-Domain Output of Single-Balanced Mixer



Differential Time-Domain Output of Double-Balanced Mixer

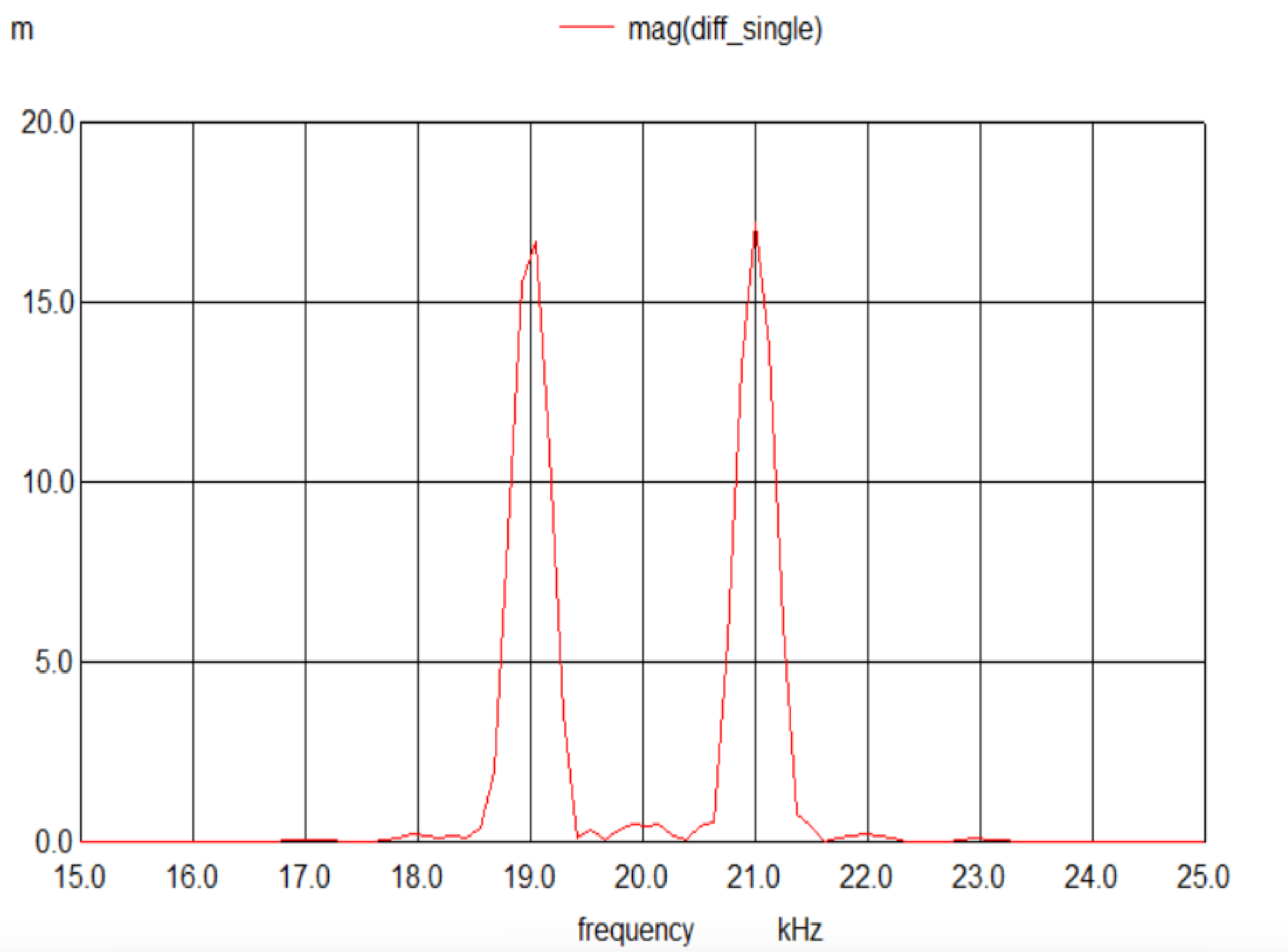


Observation:

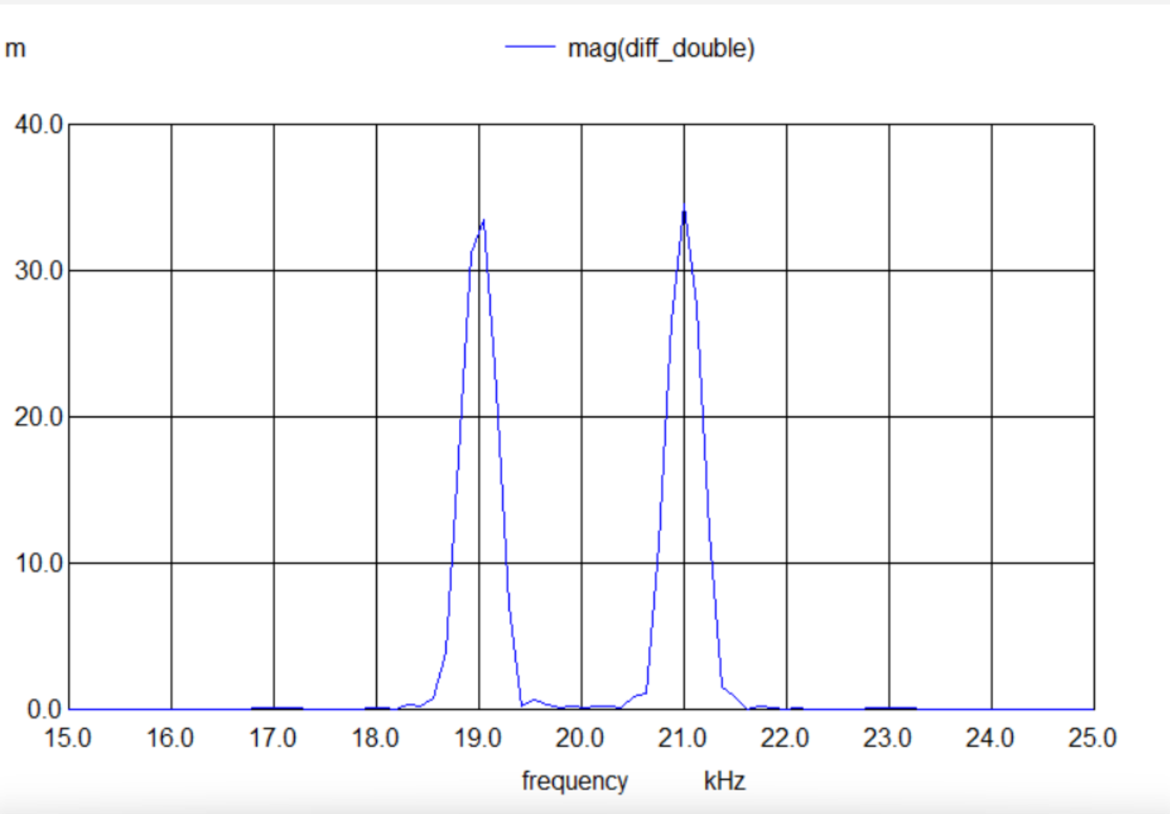
Extracting the differential AC-coupled signal highlights two major performance differences in the time domain. First, the single-balanced output (Figure 7) exhibits a jagged, thickened modulation envelope caused by residual high-frequency LO switching transients that the single-bridge topology cannot fully cancel. Second, the double-balanced output (Figure 8) yields a much cleaner, perfectly symmetric envelope with significantly higher amplitude. By utilizing all four quadrants of the LO and RF signals, the double-balanced mixer effectively doubles the voltage swing (reaching roughly $\pm$90 mV compared to the single-balanced $\pm$48 mV), demonstrating vastly superior conversion gain.

Frequency-Domain Analysis (Carrier Suppression):

FFT Spectrum of Single-Balanced Mixer



FFT Spectrum of Double-Balanced Mixer



Observation:

The Fast Fourier Transform (FFT) provides definitive mathematical proof of perfect carrier suppression. In the single-balanced spectrum (Figure 9), the desired sidebands appear at 19 kHz and 21 kHz with magnitudes of approximately 17 mV. However, a distinct, unwanted energy bump remains visible at exactly the 20 kHz center frequency, proving that LO carrier leakage is still occurring.

Conversely, the double-balanced spectrum (Figure 10) completely obliterates the 20 kHz carrier. The center frequency is a perfect flatline (zero magnitude), leaving only the pure sidebands, which have doubled in magnitude to roughly 34 mV. This proves the 4-transistor ring successfully traps and cancels the LO feedthrough entirely in hardware.

Conclusion:

The simulated results successfully validate the rigorous theory behind double-balanced CMOS ring mixers.

Simulation Methodology and Netlist Troubleshooting:

During the initial simulation phase, the eSim GUI KiCad-to-Ngspice converter encountered a parsing error when compiling the custom transistor parameters. The engine returned a fatal SPICE error (can't find model 'mosfet_n'), resulting in a failure to launch the Python plotter.

To resolve this software limitation, the simulation was debugged and executed manually using the following methodology:

Netlist Modification: The generated output netlist **(.cir.out)** was manually accessed and edited. To ensure proper convergence and switching behaviour, a custom SPICE model directive was injected directly into the netlist code: **.model mosfet_n NMOS (level=1)** This explicitly defined an ideal N-channel MOSFET structure for the switching ring.

Terminal Execution: The modified netlist was then compiled and run directly through the Ngspice command-line terminal, bypassing the GUI. The transient and frequency-domain differential vectors were mathematically calculated and plotted using native Ngspice terminal commands.

Reference(s):

1. Razavi, B. (2017). *Design of Analog CMOS Integrated Circuits* (2nd ed.). McGraw-Hill Education. *(Reference for standard passive mixer theory, conversion gain, and LO feedthrough characteristics).*

Title: RF Microelectronics (2nd Edition) - Chapter 6: Mixers

Author: Behzad Razavi

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2. Lee, T. H. (2004). *The Design of CMOS Radio-Frequency Integrated Circuits* (2nd ed.). Cambridge University Press. *(Reference for double-balanced ring topology and RF port-to-port isolation).*