ECE 145B/218B, Lab Project 2: Unbalanced Transistor Mixer

January 10, 2024

Precautions

Precautions to avoid instrument damage

(a) Observe static precautions when working with the network analyzer or spectrum analyzer. Wear the wrist strap.

(b) Never connect a network analyzer or spectrum analyzer directly to a circuit carrying dc. Make sure your circuit is dc blocked, or you will destroy the instruments..

Safety precautions

(a) Safety note: please be very careful with the X-acto razor-blade knives. Use the same level of care you would use with a very sharp kitchen knife ! We want no injuries.

(b) Common solder is tin-lead and is toxic. If ingested, lead accumulates in your body and slowly and progressively causes brain damage as well as damage to other organs. The shop sells non-lead-containing solder. ***Do not bring lead-containing solder into the lab.*** That means, do not purchase solder at Radio-shack or other vendors unless you very carefully check its metal composition. The new non-lead solders have a higher melting point, which makes soldering harder, particularly soldering to ground planes. Use a higher-power (hotter !) iron for soldering to the ground plane.

(c) In case some student fails to follow the solder rules above, ***do not eat or bring food into the lab, wash your hands immediately after leaving the lab***, and sweep up and dispose of any solder debris. ***Do not use solder-suckers for desoldering, as these spray a fine powder of solder all over the room***. Horribly toxic if some fool uses them with lead solder ! Use desoldering wick (braid) instead; it is better anyway.

(d) Basic rules for electrical safety apply. Circuit voltages are low (~5-15 Volts) but avoid bringing in high-voltage DC supplies, use common caution in plugging in 120 V connections, do not stand in or work around water, and do not work with electrical equipment with bare feet.

(e) students who violate these precautions will receive a lab grade of zero.

Background and Suggested Approach.

Every consideration has been made to make this lab project as simple as possible. To manage your very limited time for this project, you will have several options as to design features to include or to skip.

While modern RF/microwave/mm-wave transistor mixers commonly use the 6-transistor Gilbert-cell configuration, the small size of the transistor package and the wiring parasitics of the complex circuit make this a poor choice for hand assembly in ece145B and ECE218B. Instead, we will design a very simple single-balanced mixer. You will pick whatever RF and LO frequency you like. Low frequencies give better RF performance and make assembly less sensitive to wiring parasitics; high frequencies make the branch line coupler and impedance matching networks easier to fit on the PCB. 1 or 2 GHz might be a good choice for the LO and RF frequencies. I suggest an IF frequency of 100 MHz, but, again, leave that to your discretion.

One major difficulty with unbalanced and single-balanced mixers is isolating the LO and RF signals, particularly if they are at similar frequencies (this making separation by filtering very difficult). As a simple (and fairly common) solution for this, we will use a branch-line coupler to separate the RF and LO signals.

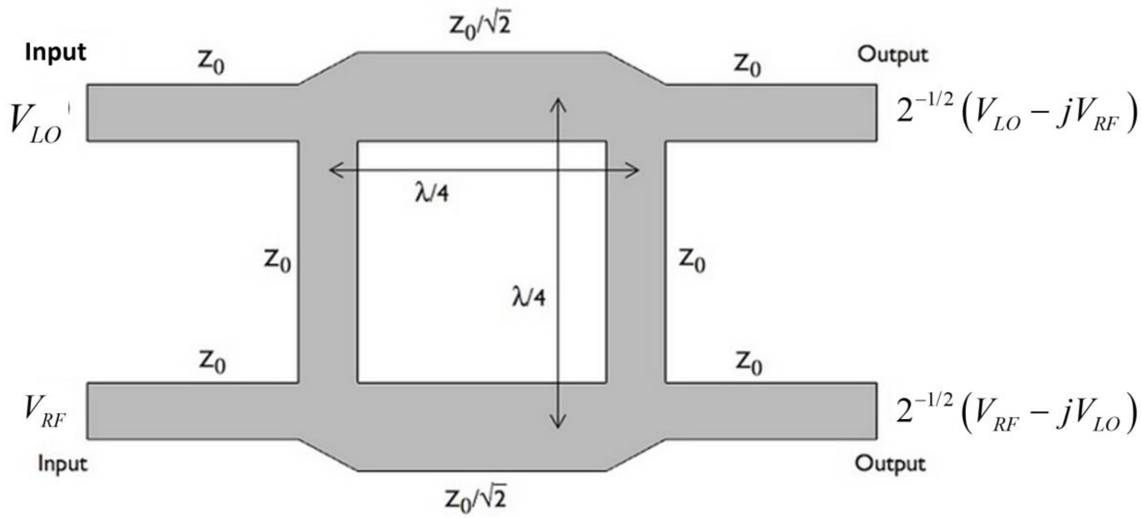

Figure 1: Microstrip branch-line coupler. The four lines are each 1/4 of a *transmission line* wavelength long.

A branch line coupler (Figure 1) is one of several physical forms of 90 degree power splitter/combiner networks. In the circuit of Figure 1, power input at the V_{LO} port will split equally between the two output ports with (neglecting some fixed phase delays), a 90 degree phase split between the two ports. By symmetry, the power input at the V_{RF} port will similarly split between the two output ports, again with a 90 degree phase relationship. At the center frequency (the frequency at which the lines are a quarter wavelength long), there is no coupling between the LO and RF ports. We pick the branch line coupler of other forms of 90 degree power splitter/combiner (e.g. Lange couplers), simply because the branch line coupler is easier to construct by hand.

Figure 2 shows the approximate suggested design and approximate suggested physical layout of the single-balanced mixer. In a typical practical design [1,2,3,4,5], two mixers would be used, one connected to each coupler port. However, to keep the design simple and easy to build, we will, as shown, use only one mixer.

To keep the design simple and easy to build, we will use an MRF901 bipolar transistor in a micro-cross package. The only available ADS model for the MRF901 assumes a small surface mount package. There will thus be some modeling error but, I hope not too much. We have found the small surface mount packages too small to work with by hand.

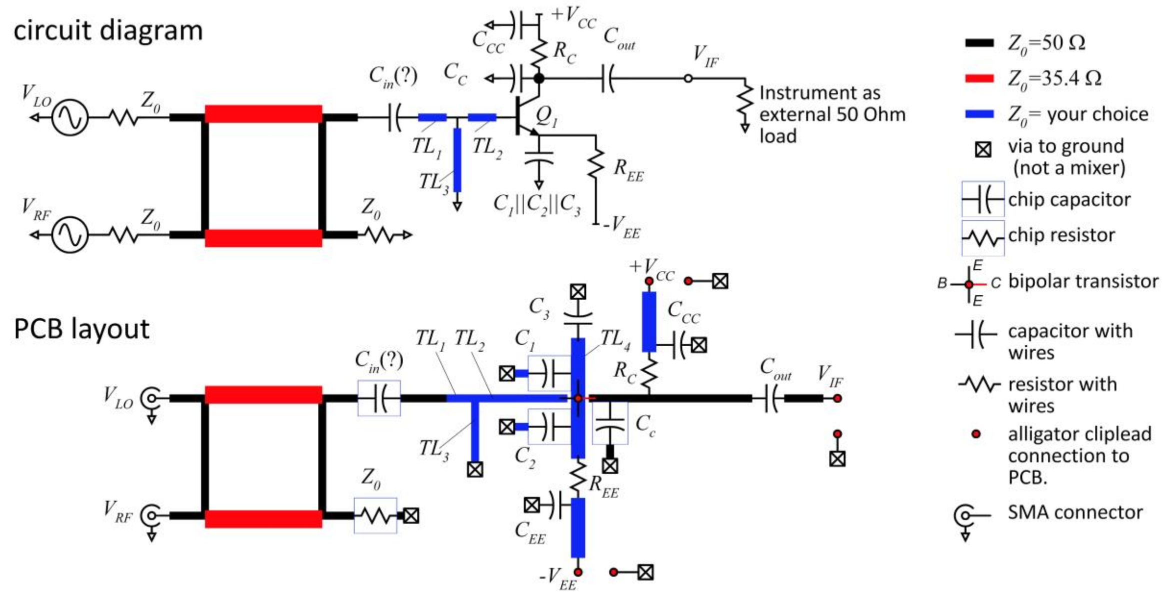

Figure 2: Schematic and PCB layout of the suggested lab project design. TL_1, TL_2 and C_{in} are optional. If inductive shunt tuning of Q1's base is not desired, then TL_3 should be $\lambda_g / 4$ long, so as to maintain the DC bias connection.

The first consideration is DC bias. Impedance-tuning microstrip line TL3 places the base of Q1 at ground. So, if it later turns out that you don't need a shunt inductive tuning element, instead of removing TL3, make it 1/4 wavelength at the LO and RF frequencies. With the base at 0V, the emitter is at $-\phi \approx -0.7$ V, hence the DC emitter current is $I_{E,DC} = (V_{EE} - \phi) / R_{EE}$. Pick $R_C = 50\Omega$ for a good S22 at the IF port. Pick V_{CC} so that the DC collector voltage $V_{C,DC} = V_{CC} - I_{EDC} R_C$ is the desired value. Pay attention to power dissipation in resistors and pick power ratings accordingly.

As we will later see, the *peak* emitter current will be perhaps two or three times $I_{E,DC}$, so pick this DC bias current accordingly: don't let the peak emitter current exceed that associated with either transistor destruction or even degraded RF performance.

In the unbalanced mixer, the LO drive voltage is much larger that the RF input voltage. Application of the LO voltage causes (Figure 3) the emitter current to vary strongly with time, varying at the frequency f_{LO}. The modulation of the collector current causes a corresponding periodic variation in the transconductance $g_m(t)$. When a small RF voltage $V_{RF}(t)$ is added to the input, the transistor output current has a component $g_m(t)V_{RF}(t)$, i.e. a mixing product. It is critical to note that the bias circuit, whether an applied voltage $-V_{EE}$ and bias resistor R_{EE} or a current source $I_{E,DC}$, maintains a constant time-average DC emitter current. Hence, as the LO voltage increases, the emitter current becomes a series of current pulses of shorter and shorter duration and larger and larger peak current, such that the charge in each pulse is simply $I_{E,DC} / f_{LO}$. Once the LO amplitude is sufficient to produce strong modulation of $I_E(t)$, the LO power need not be further increased.

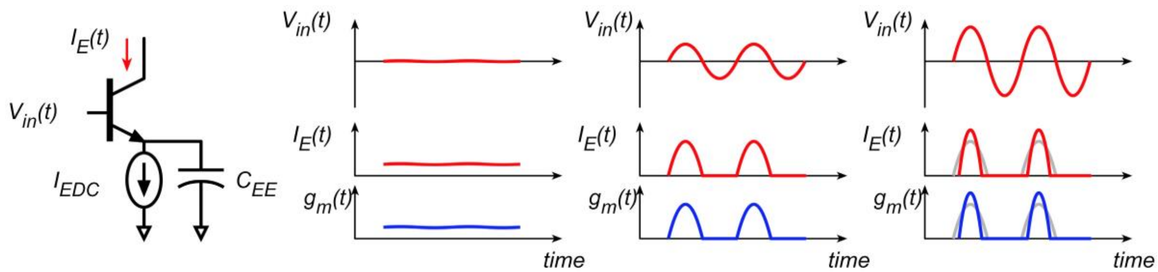

Figure 3: Basic unbalanced mixer operation. With a large LO input at Vin(t), the transistor current becomes a series of pulses with repetition frequency f_{LO}, causing g_m to also vary periodically with time. When a small RF voltage $V_{RF}(t)$ is added to the input, the transistor output current has a component $g_m(t)V_{RF}(t)$, i.e. a mixing product.

Returning to Figure 2, the function of various circuit elements can now be described, and design considerations noted. C_{EE} and C_{cc} are simply supply bypasses; their value is not critical. C_{in}, TL_1, TL_2, and TL_3 are an input LO or RF impedance-matching network. Though this will be discussed later, note that if C_{in} is not needed for impedance matching, it can be omitted; there is no need for a DC block, as the base is at DC ground. Small chip capacitors C_1 and C_2 short-circuit Q_1's emitter to ground at f_{LO} and f_{RF}; these capacitors must be placed very close to the transistor. Capacitor C_3 is much larger and serves to ensure that the impedance from the emitter of Q1 to ground is much smaller than $1/g_{m1}$ even at f_{IF}; otherwise the IF response will suffer a low-frequency cutoff. Inductance in series with C_3 is not as of great concern as would be inductance in series with C_1 and C_2. The capacitor C_C must be carefully chosen. It serves to AC-short the collector of Q1 to ground at f_{LO} and f_{RF}, preventing coupling of these frequencies to the IF output, but this capacitor must have an impedance much larger than the IF load impedance Z_O at the frequency f_{IF} so as to avoid attenuating the IF output.

The transmission-line TL_4 serves no electrical purpose, but it does serve a physical one: providing a conductor to solder together the emitter of Q1 to the capacitors C_1 and C_2 with minimal series inductance. TL_4 should otherwise be kept as short as possible, and, or course, it should be included and modelled correctly in the mixer simulations.

C_{out} is a DC blocking capacitor for the IF output. Its capacitive reactance must be small in comparison with Z_0 at f_{IF} .

Caution: before simulating the circuit with LO and RF inputs, the basic circuit should be simulated for in-band and out-of-band small signal stability, and stabilization added as necessary. ***Comment:*** checking stability with no LO present is in fact necessary but not sufficient for real mixer design. Given limited time, we will not attempt to stabilize in the presence of LO drive.

You have been given two launcher blocks by the shop. Use these for the RF and LO connections. Twisted pair connections are acceptable for the power supply connections. If the IF frequency is 100 MHz or less, you can connect to the IF output using either a *short (2-3 inch)* alligator clip lead connecting to a coaxial cable. **Or, you can use a lower-quality solder-on or screw-on BNC or SMA connector**.

Some citations on branch-line couplers and branch-line mixers:

The Assignment

Give the very short time available, and the complexity of the project, whether for 145B or 218B you have the option of including or omitting several design features.

The LO power should be at most 0 dBm. Possibly you can make the mixer work well with -5 dBm LO power. More that 0 dBm LO power is likely to simply over-drive the transistor, driving it into saturation at the peak of the LO drive waveform. This should be avoided.

<u>Option 1:</u> Your minimum assignment is to construct the above circuit, omitting the impedance matching elements TL_1, TL_2 and C_{in} and setting TL_3 to $\lambda_g / 4$ long, so as to maintain the DC bias connection. In this case, you have provided no impedance matching at the LO or RF frequencies. You should pick the transistor $I_{E,DC}$ and $V_{CE,DC}$, should simulate the conversion gain at the (f_{LO}, f_{RF}, f_{IF}) combination you choose, build the circuit, measure its performance, adjust the design as needed, and report the measured and simulated performance.

<u>Option 2:</u> Well-designed double balanced mixers use impedance-matching at the LO to reduce the needed LO power and impedance matching at the RF to either increase the RF-IF conversion gain or (better) to reduce the mixer noise figure. In an unbalanced mixer, we can't independently tune the LO and RF impedances, so will not attempt to tune for lowest LO power. We *can* however tune the network TL_1, TL_2, C_{in} and TL_3 to provide an impedance match at f_{RF} to maximize the RF-IF conversion gain. *However,* this tuning must be done on the RF port *in the presence of the applied LO signal.* This is a more sophisticated simulation in ADS. The mixer design guide in ADS shows you how to do this. Please ask the TA for guidance.

<u>Option 3:</u> I doubt you will have time for this, and I've not even done it myself in mixer design, but the *smart* way to design a mixer is to tune the RF port for *minimum noise*

figure. To do this, noise must be simulated while the circuit is operating as a mixer. I believe that modern versions of ADS can perform this simulation given an adequately powerful computer. I am far from sure that this would be feasible with the computers presently available in the ECI lab.

Construction: The mixer should be constructed on a Duriod board, with launcher blocks and SMA connectors for the LO and RF connectors

Measurement: With the chosen value of f_{LO} and P_{LO} applied, the conversion gain should be measured as a function of f_{IF}, of course varying f_{RF} according to $f_{RF} = f_{LO} \pm f_{IF}$, varying f_{IF} over at least a $\pm$ 50 MHz frequency range

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[1] https://edadocs.software.keysight.com/display/genesys2010/Diode+Branch+Line+Single+Balanced
[2] https://ieeexplore.ieee.org/abstract/document/966848
[3] https://digital-library.theiet.org/content/journals/10.1049/el.2012.0402
[4] https://ieeexplore.ieee.org/abstract/document/4242329
[5] https://ieeexplore.ieee.org/abstract/document/1489619