LABORATORY REPORT - CHAPTER 5

v7.6

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Total Grade	/100

Record all your measurements and write all your answers in the boxes provided.

Preliminary Work

1. Transmitter Amplifier

i. A tuned RF amplifier that acts as the transmitter amplifier of TRC-11 can be built using a BJT, Q30. BJT to be used is a more powerful NPN transistor, 2N2222. Inspect the datasheet given in 347. It can handle currents up to 600 mA and voltages up to 40 V. It can dissipate up to 625 mW power at room temperature. These values are considerably high compared to KSP10 used earlier. Refer to the circuit given in Fig. 1. It is a Class-A power amplifier intended to drive an antenna. R_L is the load to be driven (it is actually the real part of the antenna impedance to be discovered later). The power delivered to R_L is the transmitted RF power into the air when the antenna is used. Actually, the output power is intentionally kept low, not the violate local RF transmission limits in this frequency band. C_{31} is a DC block capacitor. L_1, L_2 and C_{37} form a impedance transformation network, that transforms R_L into an optimal impedance for the transistor.

The supply voltage, V_S, of this is to be varied to according to the audio signal to be transmitted. When the supply voltage is changed the RF signal output voltage is also changed accordingly. To change the supply voltage we utilize another BJT, Q31, forming the modulation amplifier. Q31 is a PNP transistor. The base bias resistors, R37 and R38 of this transistor is selected so as to keep the voltage V_S at 7 V. This choice allows the supply voltage to be varied between 7+5=2 V to 12 V, when a time varying signal is applied to the base of Q31.

A DC analysis of the transmitter and modulation amplifier can be made using the schematic shown in Fig. 2, obtained by short-circuiting inductors and open circuiting capacitors. Biasing resistors, R_{30}, R_{31}, R_{32}, R_{37}, and R_{38} can be calculated after deciding on the DC operating point of the transistors, Q30 and Q31, while considering the variations in β's of the transistors. To find the values of resistors, we set the operating point as V_S=7 V and V_{E1}=2 V with V_{DD}=12 V. We note that now V_{CE1}=$-V_{CE2}$=5 V. This choice allows V_S to vary between 2 V to 12 V with equal 5 V swing in both directions. We also set I_{C1}=I_{C2} in the 20 mA to 40 mA range. In idle conditions DC power dissipations on Q30

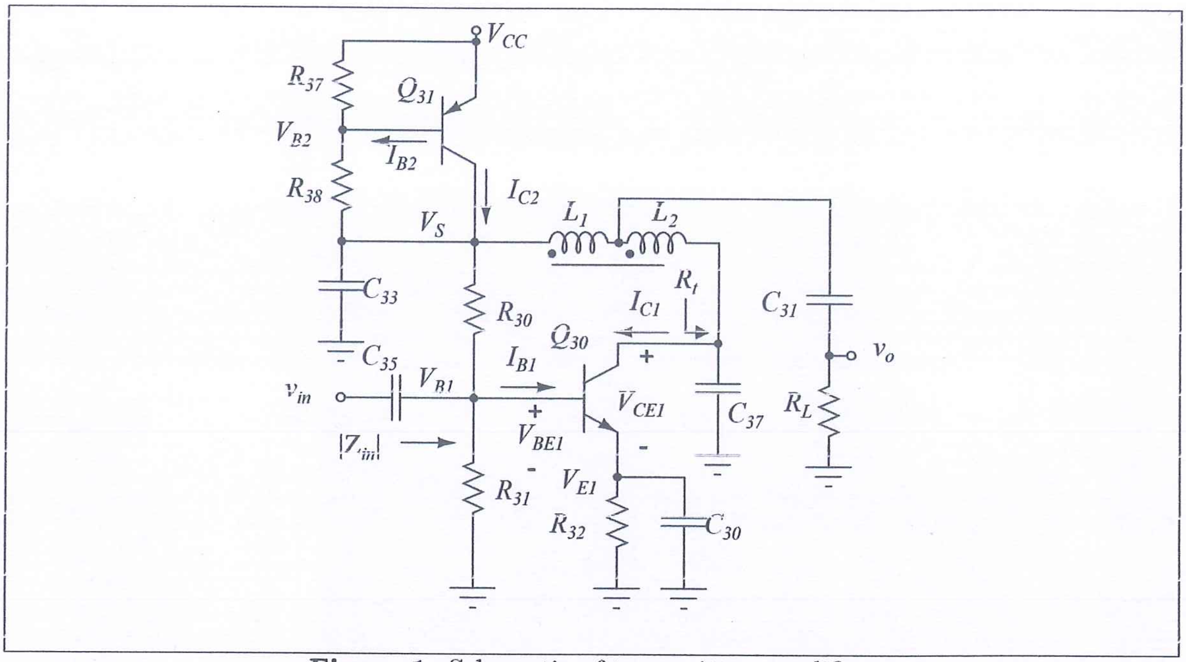

Figure 1: Schematic of transmitter amplifier.

and Q31 are $V_{CE1}I_{C1}$=$-V_{CE2}I_{C2}$ is in the range 100 mW to 200 mW, within the allowed range of the transistors.

Since β of transistors may vary from device to device, we need to design with a little dependence on β variations. For this purpose, it is a good idea to choose I_{30}=I_{38} about 10 to 20 times smaller than I_{C1}=I_{C2}. Let us choose I_{30}=I_{38}=1.3 mA. Assuming the base-emitter voltages of transistors are approximately 0.75 V, we have V_{B1}=V_{E1}+0.75=2.75 V, and $V_{B2} = V_{CC} - 0.75$=11.25 V. We can now find the values of resistors:

$$R_{38} = \frac{V_{B2} - V_S}{I_{38}} = \frac{11.25 - 7}{1.3} = \frac{4.25}{1.3} = 3.27\ K\Omega \tag{1}$$

We choose the closest standard value of R_{38}=3.3 KΩ. Similarly, R_{30} can be found from

$$R_{30} = \frac{V_S - V_{B1}}{I_{30}} = \frac{7 - 2.75}{1.3} = \frac{4.25}{1.3} = 3.27\ K\Omega \tag{2}$$

Hence we choose R_{30}=3.3 KΩ as well. From the datasheet of BC556B, we see that β=h_{FE} can vary between 180 to 460. We choose a typical value of β_2=320. The current in R_{37} is

$$I_{37} = I_{38} - I_{B2} = 1.3\text{mA} - \frac{I_{C2}}{\beta_2} \tag{3}$$

The resistance R_{37} can be found from

$$R_{37} = \frac{V_{CC} - V_{B2}}{I_{37}} = \frac{0.75}{I_{37}} \tag{4}$$

Similarly, the resistance R_{31} can be found from

$$R_{31} = \frac{V_{B1}}{I_{31}} = \frac{V_{B1}}{I_{30} - I_{C1}/\beta_1} = \frac{2.75}{1.3\text{mA} - I_{C1}/200} \tag{5}$$

with a typical β_1=200, since its β can be anywhere between 75 to 325.

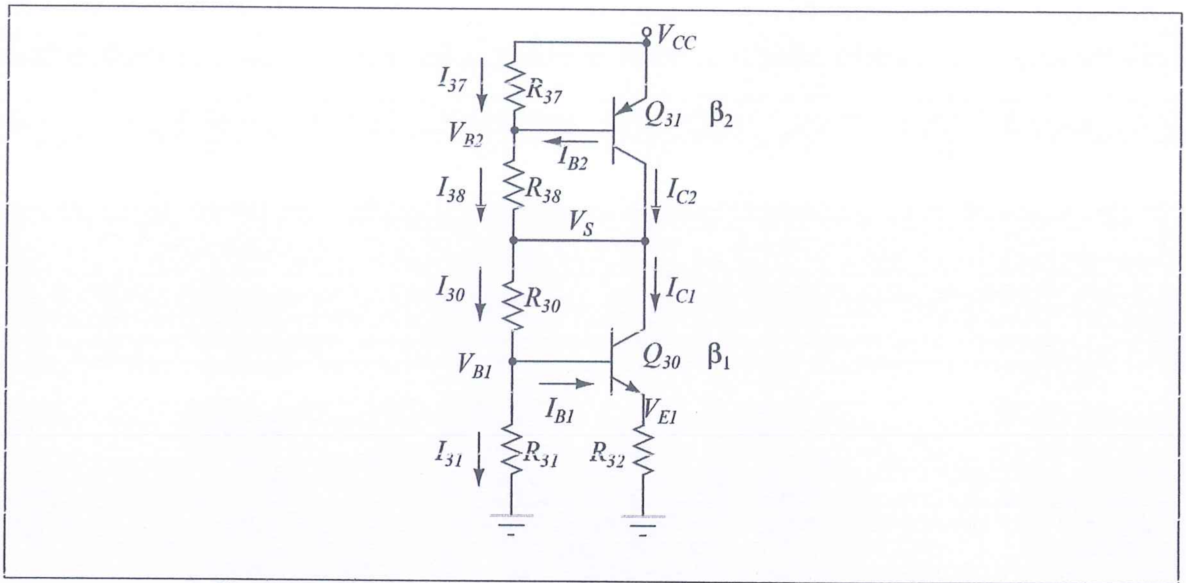

Figure 2: Schematic of transmitter amplifier for DC analysis.

The emitter resistance of Q30 can be found from

$$R_{32} = \frac{V_{E1}}{I_{C1}} = \frac{2}{I_{C1}} \tag{6}$$

Choose I_{C1}=I_{C2} in the 20 mA to 40 mA range and calculate the values of R_{31}, R_{37}, and R_{32}. Note that if the currents are specified in mA, the resistors are found in KΩ. Choose the closest standard values.

Transmitter amplifier: I_{C1}=I_{C2}= 30mA (See Appendix 1 for calculations)

R_{31}= 2.2kΩ R_{37}= 680Ω R_{32}= 68Ω

1.1. GRADE:

2. The value of the capacitor, C_{30}, can be determined by

$$C_{30} > \frac{10}{2\pi f_0 R_{32}} \tag{7}$$

since this bypass capacitor is supposed to short-circuit R_{32} at the operating frequency of f_0=27 MHz. It is a good idea to choose a capacitor close to this limit, but not much higher. Choose the closest standard value. The value of the decoupling capacitor, C_{33}, can be determined from

$$C_{33} > \frac{10}{2\pi f_0 |Z_d|} = 58\text{nF} \tag{8}$$

where $|Z_d|$ is the required impedance of V_S, approximately 1 Ω. Choose C_{33}=68nF.

Transmitter amplifier: C_{30}= 1.0 nF (See Appendix 2 for calculations)

1.2. GRADE:

3. The optimal load resistance for the transistor, Q30, is given by

$$R_{opt} = \frac{V_{CE1}}{I_{C1}} = \frac{5}{I_{C1}} \tag{9}$$

Find the value of R_{opt}.

R_{opt}= ≈170 Ω (see Appendix 3 for calculations)

1.3. GRADE:

4. Coupled inductors L_1 and L_2 along with C_{37} form an impedance transformation network that transforms R_L to a resistance R_t close to the optimal resistance, R_{opt}. Unfortunately, simple analytical expressions to find the component values do not exist. Instead, one can use LTSpice to determine the values. The transformation ratio can be found using AC

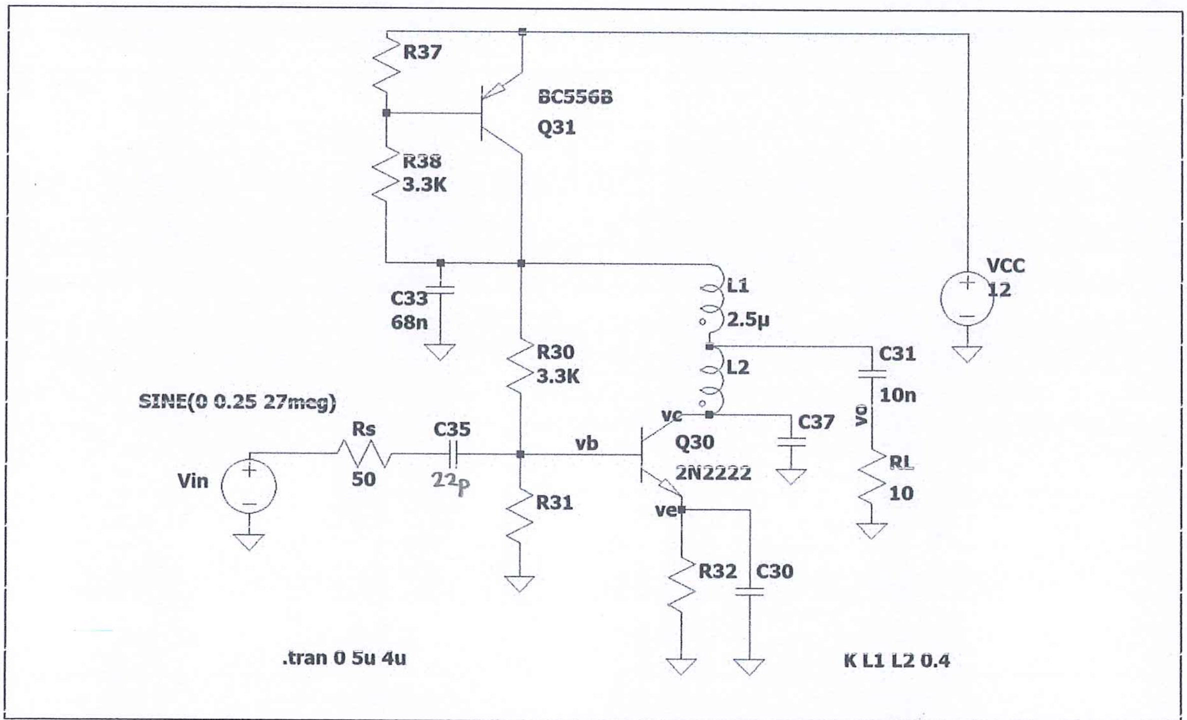

Figure 3: LTSpice schematic of transmitter RF amplifier.

analysis in LTSpice. One can find the load impedance as a function of frequency by plotting $-V(vc)/Ic(Q1)$ on a linear scale (not dB). L2 and C37 value should be adjusted so that the phase of the load impedance is zero (so that it is resistance) at 27 MHz. The value of the transformed resistance, R_t, can be read as the magnitude of $-V(vc)/Ic(Q1)$.

L_2 (nH)	C_{37} (pF)	R_t (Ω)
729	56	757
595	68	524
490	82	368
395	100	250
322	120	173
248	150	110

Table 1: Values of transformation network at 27 MHz for L_1=2.5 μH and k=0.4.

The results of a number of such simulations are shown in the Table 1. (You do not need to repeat the simulations). Choose most suitable values of L_2 and C_{37} from the table so that $R_{opi} \approx R_t$.

Use these values in the LTSpice. LTSpice already has the model for the npn transistor, 2N2222 and the pnp transistor, BC556B. Enter a schematic as shown in Fig. 3 using the calculated values of resistors and capacitors. Note that L1 and L2 are coupled inductors with "K L1 L2 0.4" statement (as SPICE directive) specifying the coupling coefficient of k=0.4 between them. Set L_1 value as 2.5μH. Insert the chosen values of L2 and C37. Perform a transient analysis to find the voltage across R_L: Simulate → Edit Simulation Cmd → Transient, Stop Time=5u, Time to start saving data=4u. Place it on the schematic window. Set the input voltage to 0.1 V peak sinusoid at 27 MHz. Increase the sinusoidal input voltage, v_{in}, (up to about 4V peak) until a distortion at the collector voltage, at vc, starts. In LTSpice simulation, make sure that the collector voltage, v_C, can span almost in the range from 2 V to 12 V without distortion. The collector current should be able to span between 0 to $2I_C$ in a nearly sinusoidal manner. You can see the collector current waveform by placing the cursor near the collector until a loop cursor appears. There may be some distortion in the current waveform. Record the maximum peak-to-peak voltage, v_{opp}, across R_L. You can measure the peak-to-peak voltage, by placing the cursor at the peaks and reading the y-values on the lower left corner.

L_2= 322nH	C_{37}= 120pF
R_t = 173 Ω	v_{opp}= 1.99V

1.4. GRADE:

5. Determine the number of turns, n_2, of L_2 from Table 2.

6. Determine the power delivered to the load resistance using

$$P_L = \frac{v_{opp}^2}{8R_L} = \frac{v_{opp}^2}{80} \tag{10}$$

It is expected to get P_L between 30 mW to 100 mW.

n_2	L_2 (nH)
3	260
4	310
5	320
6	380
7	450
8	540
9	680

Table 2: Number of turns using 0.35 mm enameled wire on T37-7 toroid, corresponding inductor values.

7. The efficiency, η, of the amplifier can be calculated by dividing the output power to the DC power of the amplifier:

$$\eta = \frac{P_L}{V_{CC}I_C} = \frac{P_L}{12I_C} \tag{11}$$

n_2= 5 turns P_L= 49.5 mW η= 0.138
(See Appendix 4 for calculations)

1.7. GRADE:

8. Refer to the datasheet of the relay in p. 397. Find the maximum current the relay contacts can carry. Find the nominal current of the solenoid with 12 V excitation.

I_{max}= 15 A $I_{solenoid}$= 30 mA

1.8. GRADE:

Experimental Work

1. Transmitter amplifier

1. The tuned RF amplifier to be mounted is the transmitter (TX) amplifier operating at 27 MHz. This circuit is given in Fig. 5. L30 is a tapped inductance. The number of turns of L2 is determined in the preliminary work. It is supposed to transform the impedance of 10 Ω to the optimum load resistance of the transistor. Cut 40 cm of 0.35 mm *enameled* wire to wind L1 and L2 on the T37-7 toroid. T37-7 is a core with an outer diameter of 0.37 inches or 9.4 mm (see p. 382). The windings should be single-layer without scrambles. Randomly wound coils do not perform well. The increased capacitance between the windings has a detrimental effect on the inductance performance. Count the turns of

L1 carefully. You should have 23 turns. It is very easy to end up with one turn more. The number of turns is the number of times the wire *passes through the toroid.* When the windings of L1 are finished, bend and twist the wire for the tap of 1 cm long. Continue winding in the same direction to complete L2. Windings should be similar to the example tapped inductor shown in the photo of Fig. 4. Cut the extra wires at both ends. Scrape

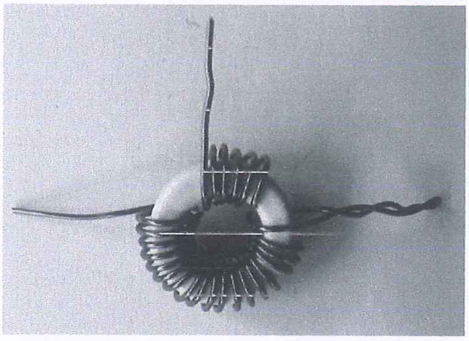

Figure 4: Photo of an example (L1 has 19 turns and L2 has 6 turns) tapped inductor (auto-transformer).

the enamel off with a knife at each end for about 3mm length without nicking the wire. If you do not strip it properly, you may have a bad solder connection, and your circuit may work only intermittently. It may be very annoying and time consuming to find and correct this later. Coat the stripped part with a thin layer of solder. If the enamel is not stripped entirely, the solder does not cover the wire smoothly, and beads of solder form on the wire. Mount L30 such that it stays a few mm's above the PCB. Make sure that L1 with a larger number of turns connects to the pin 1, the tap of the inductor connects to the pin 2, and the L2 with a smaller number of turns connects to the pin 3. Solder its leads. Using the multimeter, check that both windings are short circuits.

2. Mount and solder the dummy load, R33.
3. Solder a piece of wire to JP30.
4. Mount and solder the capacitor C31.
5. Mount and solder a loop of wire to the test point TP32.
6. Mount and solder a loop of wire to the test point TP33.
7. Mount the relay, K30, in its place and solder.
8. Mount the diode, D31, and solder it. This reverse biased diode is needed for every relay coil, to protect the mechanical switch used to turn on the relay. Without the diode, the service life of the switch may be reduced severely.
9. Solder a wire to the jumper JP90. This wire applies power to the relay and hence the relay contacts connect the center tap of the inductor L30 to the dummy load R33.
10. Apply power to TRC-11. You should hear the click sound of the relay upon power up connecting TP32 to the dummy load through C31. Disconnect the power.
11. Mount and solder the resistors, R35 and R36. Solder a looped wire to TP31. They are needed in the testing phase of the receiver.

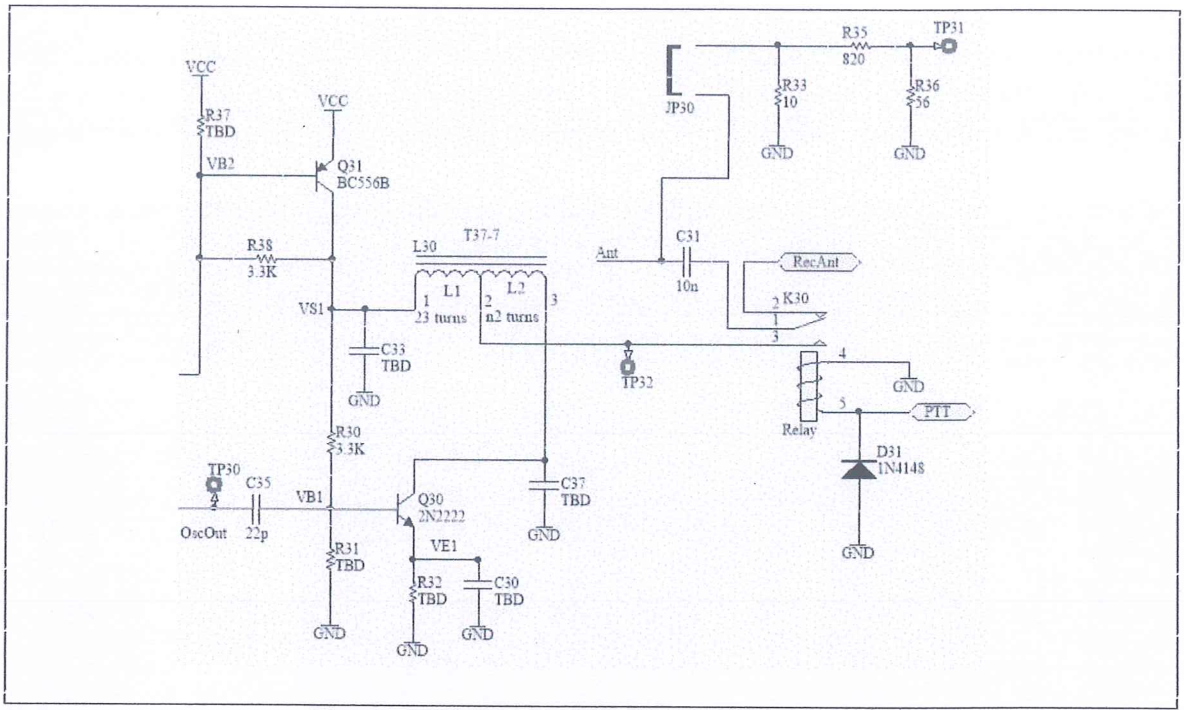

Figure 5: Schematic of transmitter amplifier.

12. Mount and solder the resistors, R30 and R38.

13. Collect the resistors R31, R32, R37, and the capacitors, C30 and C33, the values of which are determined earlier. Mount and solder them.

14. Place C37 with the value you found in its place, but do not solder it yet. Its value is critical, you may need to change it with a smaller or larger standard value.

15. Mount and solder the NPN transistor, Q30, watching the orientation of the pins.

16. Mount and solder the PNP transistor, Q31, watching the orientation of the pins.

17. Solder a loop of wire to the test point, TP30.

18. Mount and solder C35.

19. The transmitter amplifier is now ready for testing. Apply the supply voltage and check the DC voltages, V_{E1}, V_{B1}, V_{B2}, and V_S. If they are not approximately equal to the intended values, debug your circuit: Check the base-emitter voltages of transistors.

20. Connect the signal generator between TP30 and GND. Use a coaxial cable with alligator clips on one end for this purpose. Connect the ground (black) lead of the signal generator to GND. Set its amplitude to 4 Vpp and frequency to 27 MHz. Connect the oscilloscope probe between JP30 and GND. If the signal is an undistorted sine wave, the value of C37 is proper. If the signal is distorted, try a capacitor with a smaller or larger value. When you are satisfied with the sine wave, you may solder C37 in its place. Measure the peak-to-peak voltage. Increase the input signal to 7 Vpp and measure the peak-to-peak output voltage. Calculate the output power in each case.

Designator	Comment	Description
C31	10 nF	Capacitor, ceramic disc, 50V
C35	22 pF	Capacitor, ceramic disc, 50V
D31	1N4148	Silicon signal diode
L30	T37-7	Toroidal core
Q30	2N2222	NPN Bipolar Transistor
Q31	BC556B	PNP Bipolar Transistor
R30,R38	3.3 K	Resistor, carbon film, axial leaded, 1/4W
R33	10	Resistor, carbon film, axial leaded, 1/4W
R35	820	Resistor, carbon film, axial leaded, 1/4W
R36	56	Resistor, carbon film, axial leaded, 1/4W

Figure 6: Bill of materials for the transmitter amplifier

V_{E1}= 2.186V V_{B1}=2.768V

V_{B2}= 11.17V V_S= 7.28V

With 4 Vpp input: v_{opp} =2.66V $P_L = \frac{(2.66V)^2}{80\Omega} \approx$ 88.4 mW

With 7 Vpp input: v_{opp}= 2.80V $P_L = \frac{(2.80V)^2}{80\Omega} \approx$ 98.0 mW

1.20. GRADE:

21. While the input is at 7 Vpp, change the signal generator frequency in 0.5 MHz steps up or down to determine the resonance frequency where the output voltage is maximum. Record the frequency and the output peak-to-peak voltage at maximum. If the signal is not maximum at 27 MHz, try changing the spacing between the coils L1 and L2 to maximize it.

f_{max}= 20.5 MHz v_{opp}= 3.36V

1.21. GRADE:

22. There is some *distortion* on the RF output signal when the transistor is driven at its limits. Distortion means that there are output signal components at integer multiples of 27 MHz, called harmonics of 27 MHz. Signals produced by transmitters at frequencies other than

the transmission frequency are called *spurious emissions* (like harmonics of the carrier), which must be very low.

With input signal at 7 Vpp, measure the amount of distortion on the output waveform using the FFT feature of your oscilloscope. With the oscilloscope probe connected to TP32, make sure that you can see a stable sinusoidal signal in the regular mode by proper triggering. Set the horizontal axis to 100 ns/div by SEC/DIV knob. Press ACQUIRE knob and set Average and Averages 16 to get a very clean and low noise signal on the oscilloscope. Now, press MATH MENU and set Operation to FFT. In the FFT screen, the oscilloscope measures and plots the frequency components of a signal with respect to frequency. Set the vertical axis to 10 dB/division by VOLTS/DIV knob. Set the horizontal scale to 25 MHz/div by FFT Zoom ×5. Set Window to Hanning. You can change the center frequency by adjusting the horizontal position knob.

Measure the difference in decibels between the amplitudes of the fundamental component at 27 MHz and the second (at 54 MHz) and third harmonic (at 81 MHz). Use CURSOR, Type MAGNITUDE, Source MATH. Adjust the cursor 1 line level to measure the peak value at the fundamental frequency (27 MHz). Set the cursor 2 level to measure the peak of the second harmonic. Read the difference from Δ (difference between the fundamental and the second harmonic). Repeat the measurement to find the difference between the fundamental and the third harmonic. Record the results.

23. Repeat the spectrum measurement when the input level is decreased to half the peak-to-peak input value (or 6 dB lower). Find out how the Δ measurements differ from the previous results.

v_{in}	7 Vpp		3.5 Vpp	
	Level (dBm)	Δ (dB)	Level (dBm)	Δ (dB)
Fundamental (27 MHz)	3.43	—	2.63	—
Second Harm. (54 MHz)	-16.2	19.6	-23.8	26.4
Third Harm. (81 MHz)	-14.6	18.0	-19.4	22.0

1.23. GRADE:

24. Your transmit amplifier is now ready :)

CHECK POINT:

Appendix Sheet

$\Rightarrow I_{C1} = I_{C2} = 30mA$ (arbitrary)

Appendix 1: $R_{31} = \dfrac{2.75V}{1.3mA - \frac{I_{C1}}{200}} = \dfrac{2.75V}{(1.3 - \frac{30}{200})mA} \approx 2391\,\Omega \Rightarrow \underline{R_{31} = 2.2k\Omega}$

$I_{37} = 1.3mA - \dfrac{I_{C2}}{\beta_2} = 1.3mA - \dfrac{30mA}{320} \approx 1.2\,mA \Rightarrow R_{37} = \dfrac{0.75}{I_{37}} = \dfrac{0.75}{1.2mA} \approx 630\,\Omega \Rightarrow \underline{R_{37} = 680\,\Omega}$

$R_{32} = \dfrac{2V}{I_{C1}} = \dfrac{2V}{30mA} \approx 67\,\Omega \Rightarrow \underline{R_{32} = 68\,\Omega}$

Appendix 2: $C_{30} > \dfrac{10}{2\pi f_0 R_{32}} = \dfrac{10}{2\pi(27MHz)(68\,\Omega)} \approx 870 \times 10^{-12} \Rightarrow C_{30} = \underline{1.0\,nF}$

Appendix 3: $R_{opt} = \dfrac{5V}{I_{C1}} = \dfrac{5V}{30mA} \approx \underline{170\,\Omega}$

Appendix 4: $P_L = \dfrac{V_{opp}^2}{80\,\Omega} = \dfrac{(1.99V)^2}{80\,\Omega} \approx \underline{49.5\,mW}$, $\eta = \dfrac{P_L}{12 I_C} = \dfrac{49.5mW}{12(30mA)} \approx \underline{0.138}$