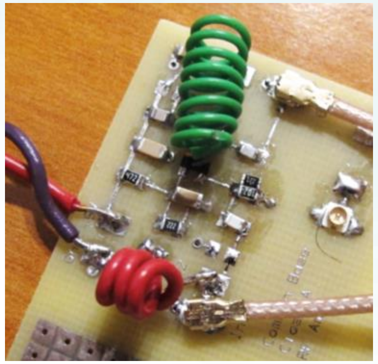
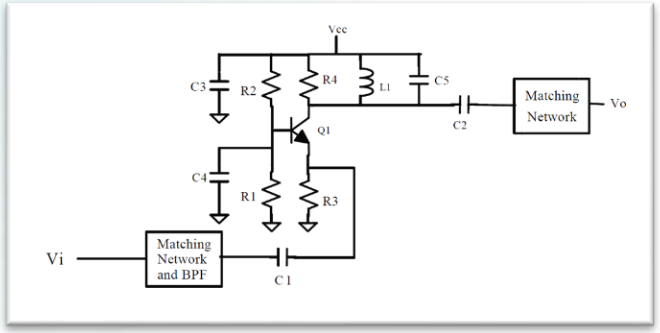
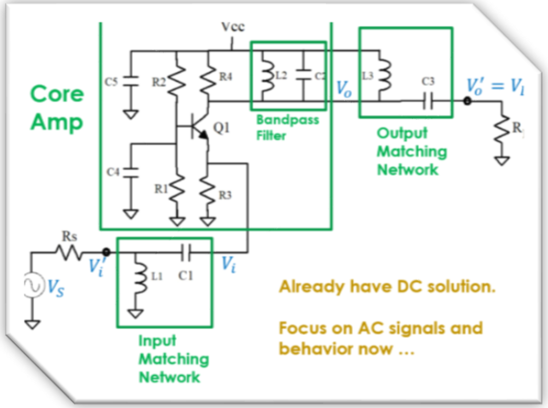
Radio Design 101
Episode 3 -- RF Amplifiers

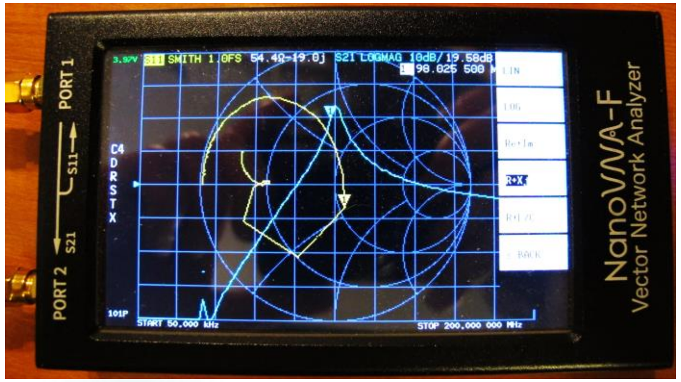
Slides downloaded from: https://ecefiles.org/rf-design/
Companion video at: https://www.youtube.com/watch?v=UUlqW-vSq9M

This episode presents a relatively complete discussion of amplifier circuits, including the electronic devices used (tubes/valves, transistors (JFET, BJT, MOSFETs)). It discusses how they're biased, and how the AC behavior is analyzed and understood in terms of gain and input/output impedances. In keeping with previous videos in this series, the focus is on radio-frequency (RF) amps, but much of the theory applies to audio amplifiers as well. A few full-circuit schematics of radios are shown for motivation, and to illustrate variations found in real-world designs.





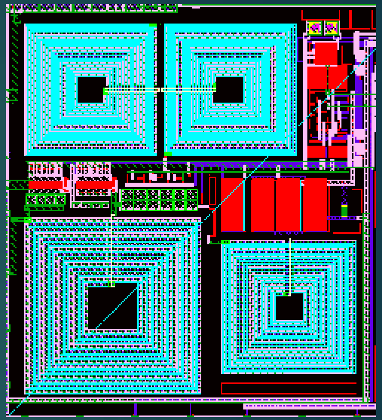


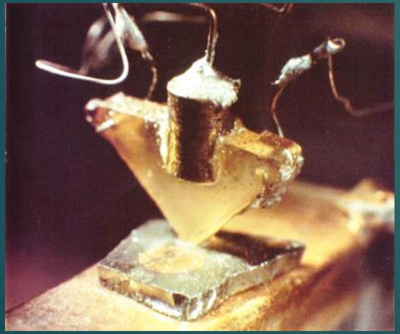


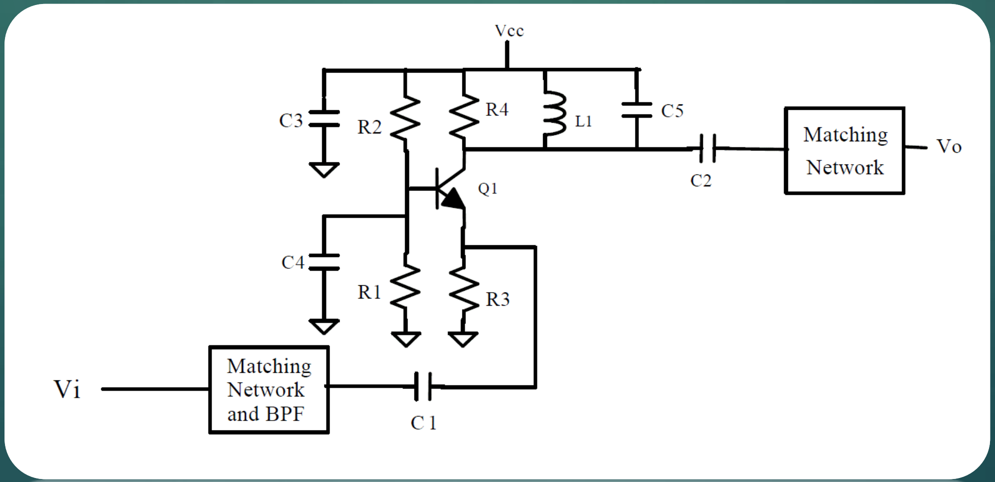
Radio Design 101

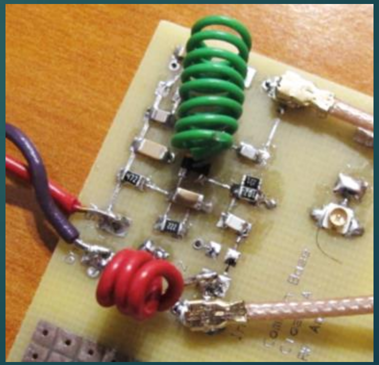
Episode 3

RF Amplifiers

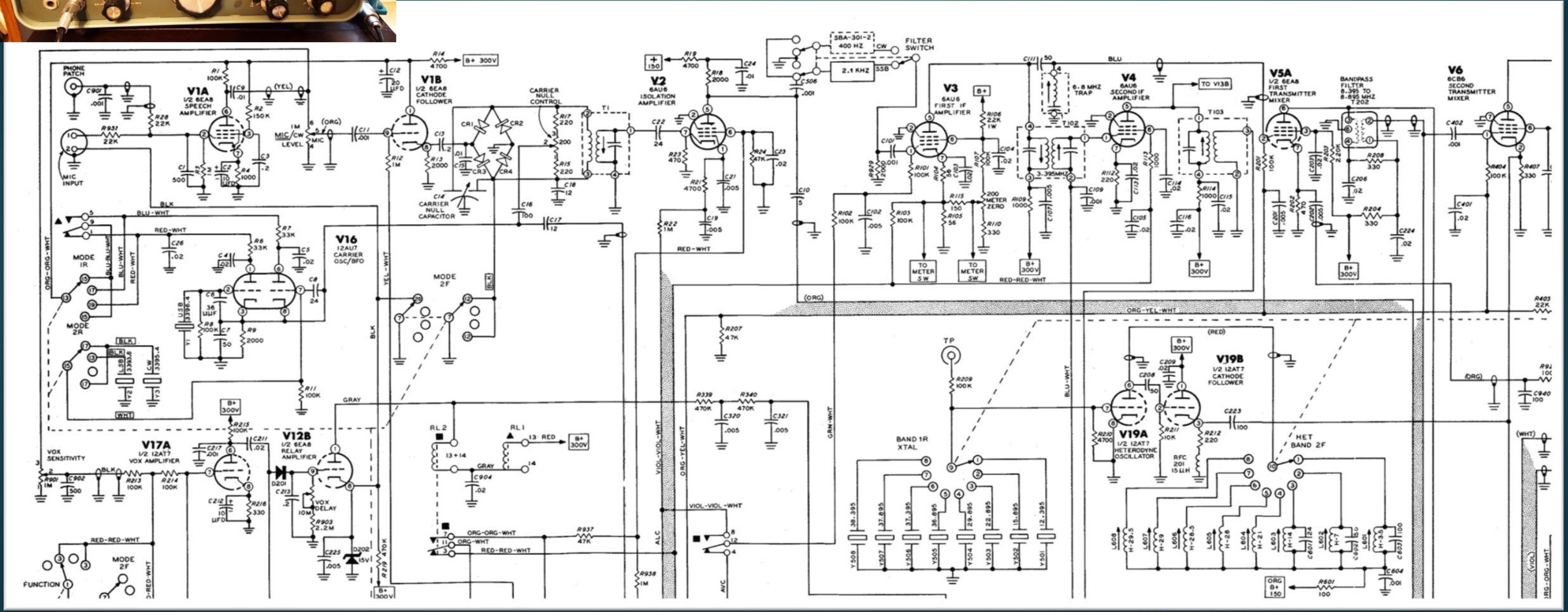




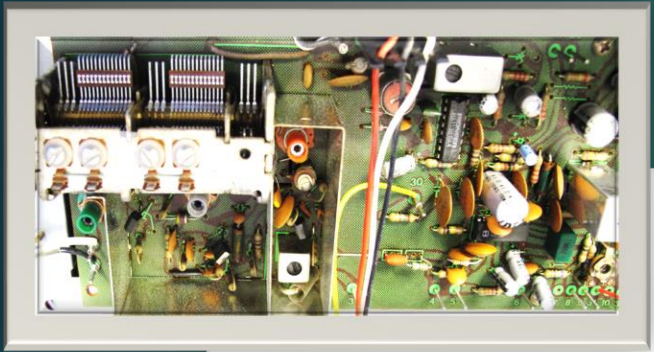


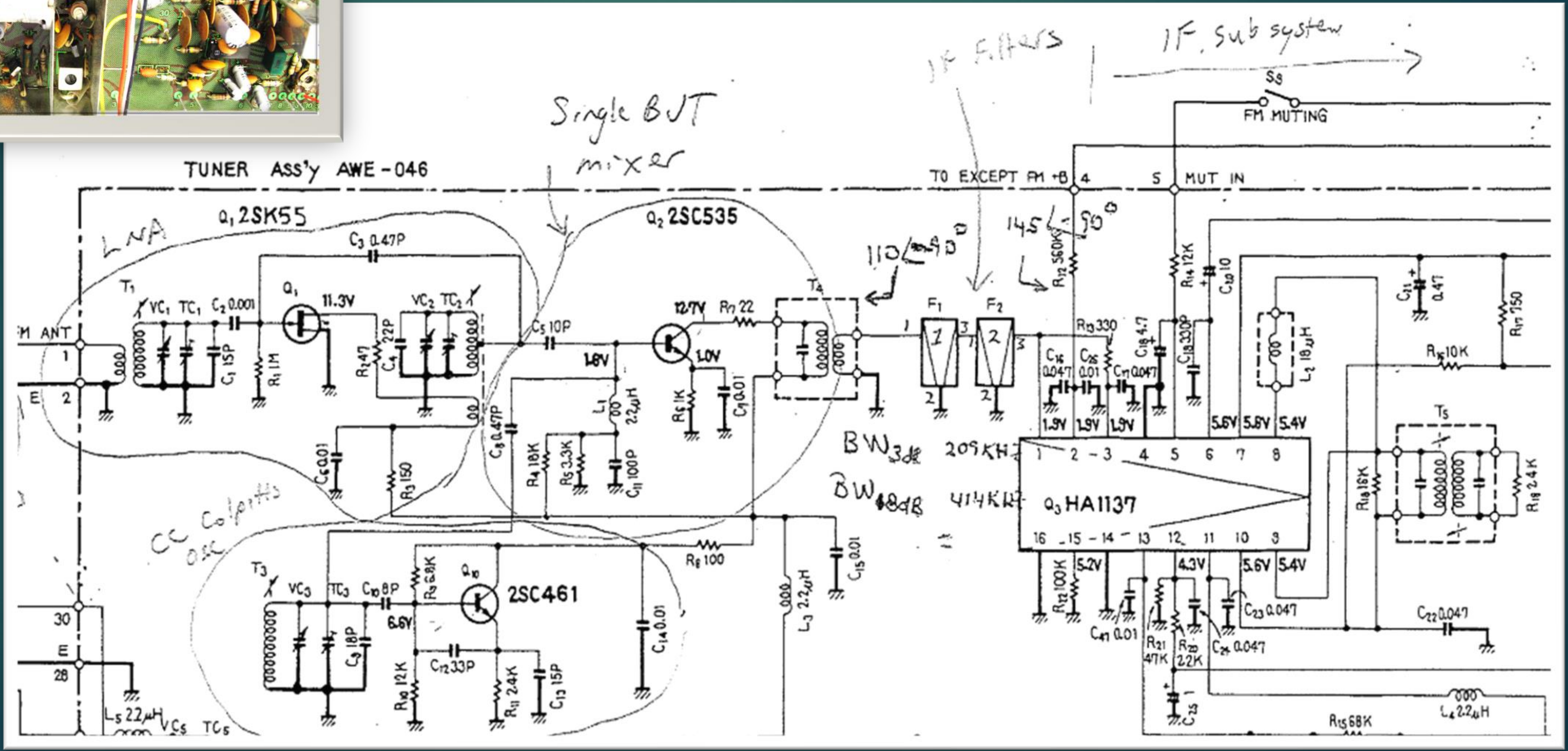


SB-102 HF SSB Transceiver



SX-535 VHF FM Receiver





Single-Chip UHF QPSK Transceiver

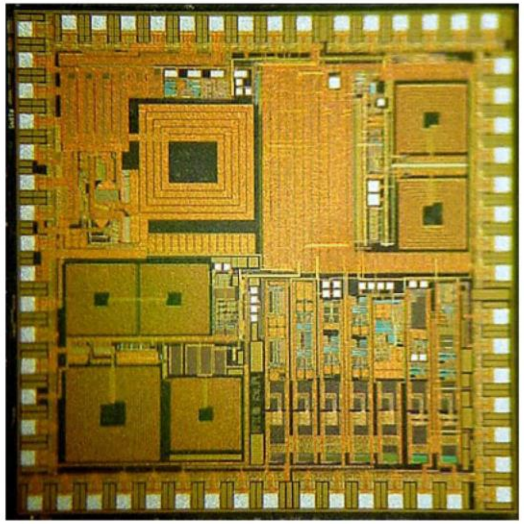


Fig. 39. *Die photo of fully integrated single-chip 100-mW transceiver.*

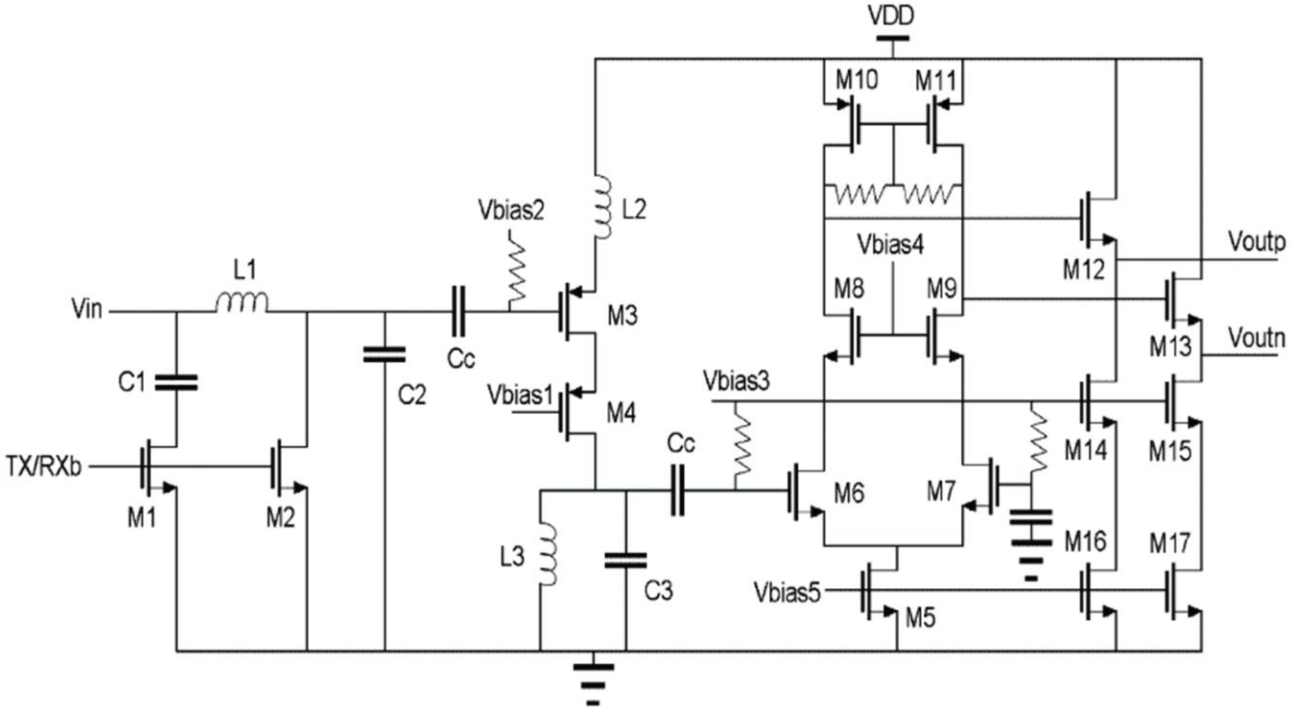


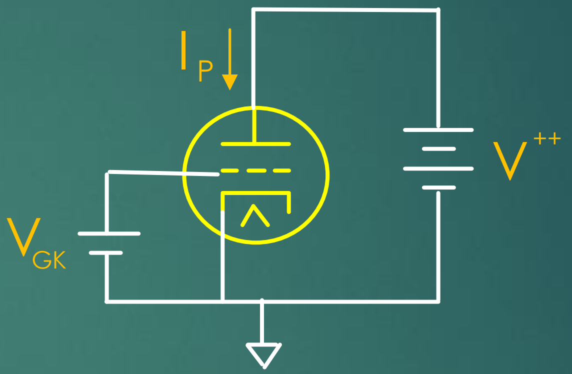
Fig. 23. *Schematic diagram of LNA with integrated T/R switch circuits.*

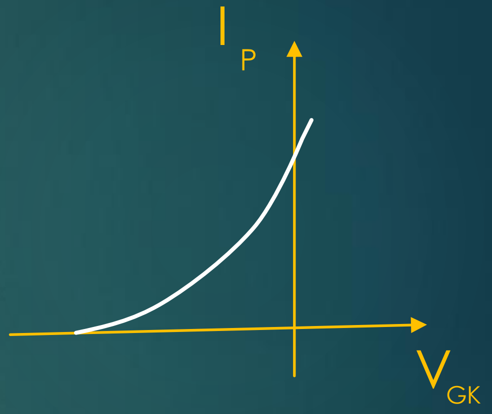
Topic Outline

- ***Triode Devices***
- ***DC Biasing***
- ***AC Gain and I/O Impedances***
- ***Amplifier Configurations***
- ***High Frequency Limitations***
- ***Data Sheets and Example Circuits***

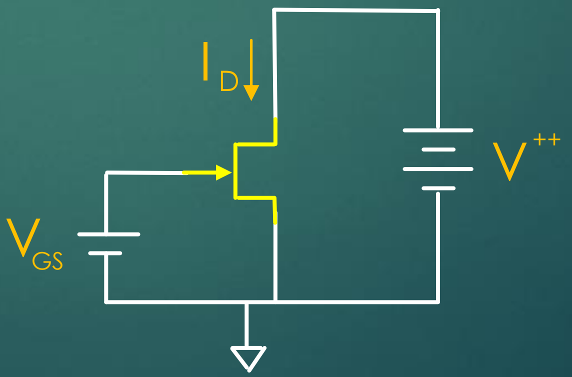
Triode Devices

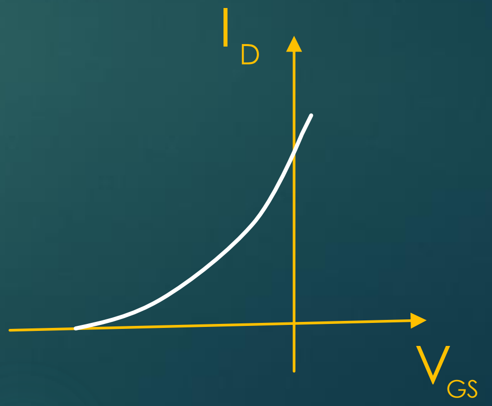
Vaccuum Tube
(or Valve)





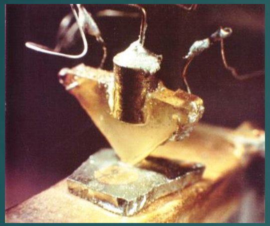
Junction Field
Effect Transistor

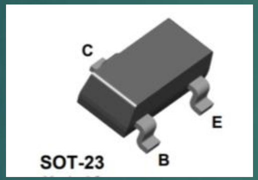


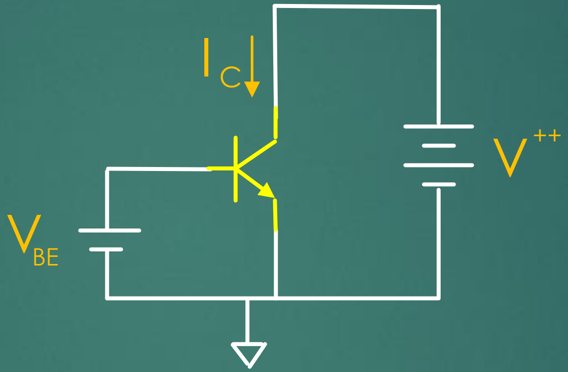


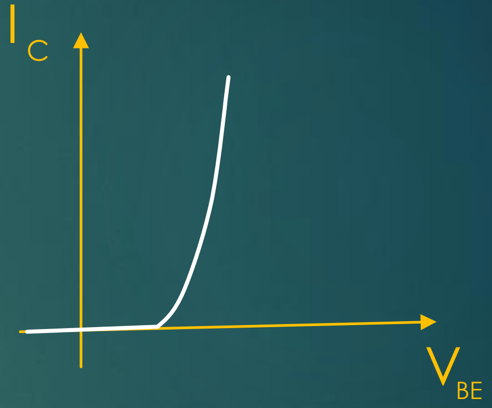
Triode Devices

Bipolar Junction Transistor

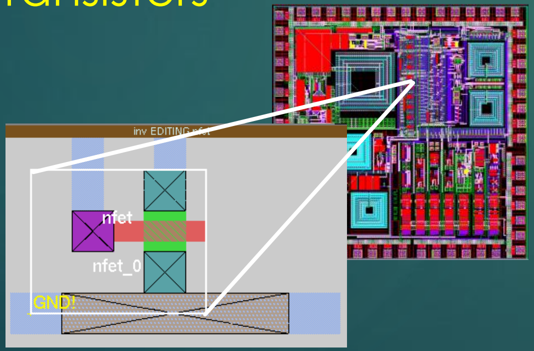


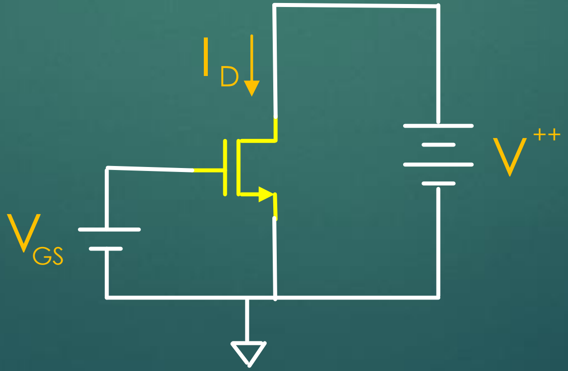


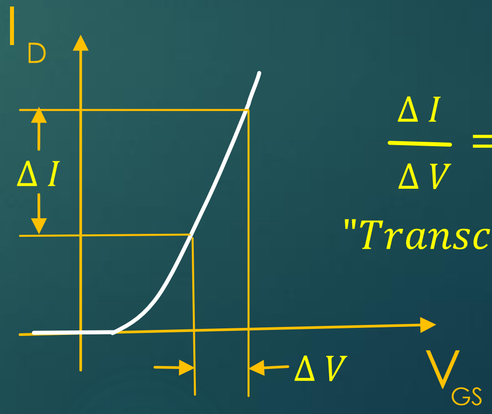




MOSFET Transistors



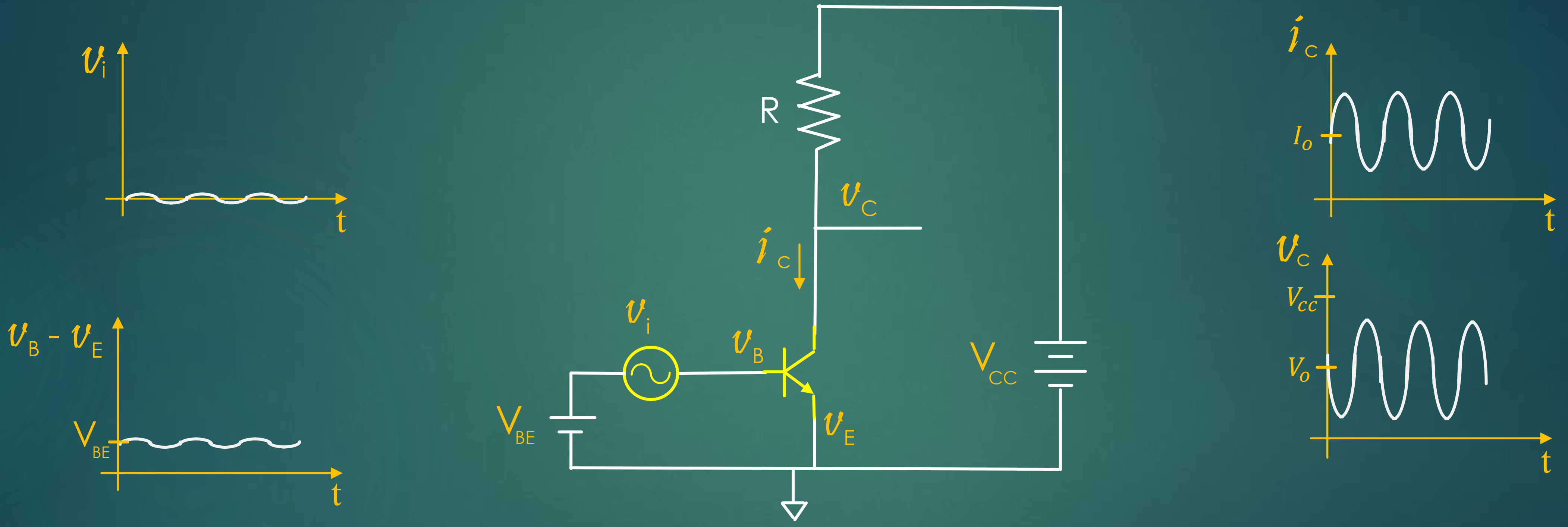




$$\frac{\Delta I}{\Delta V} = g_m$$

"Transconductance"

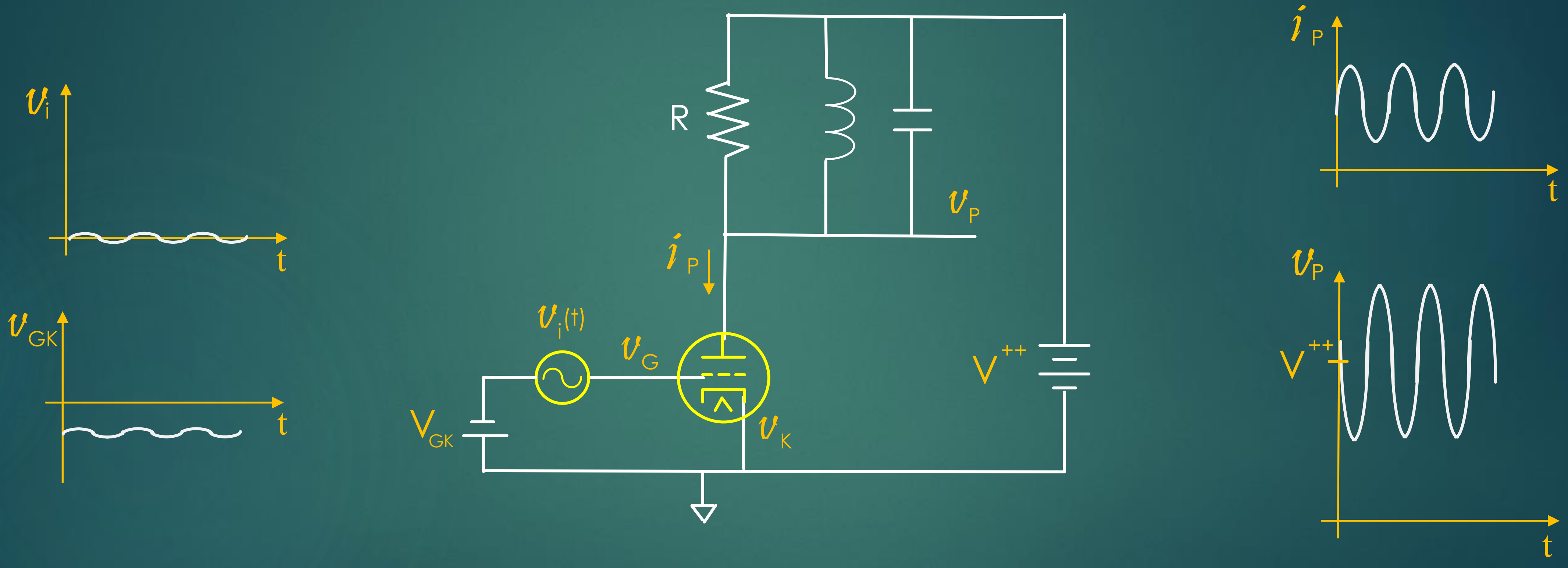
Basic Amplifier Concept



$$A_v = -g_m \text{R}$$

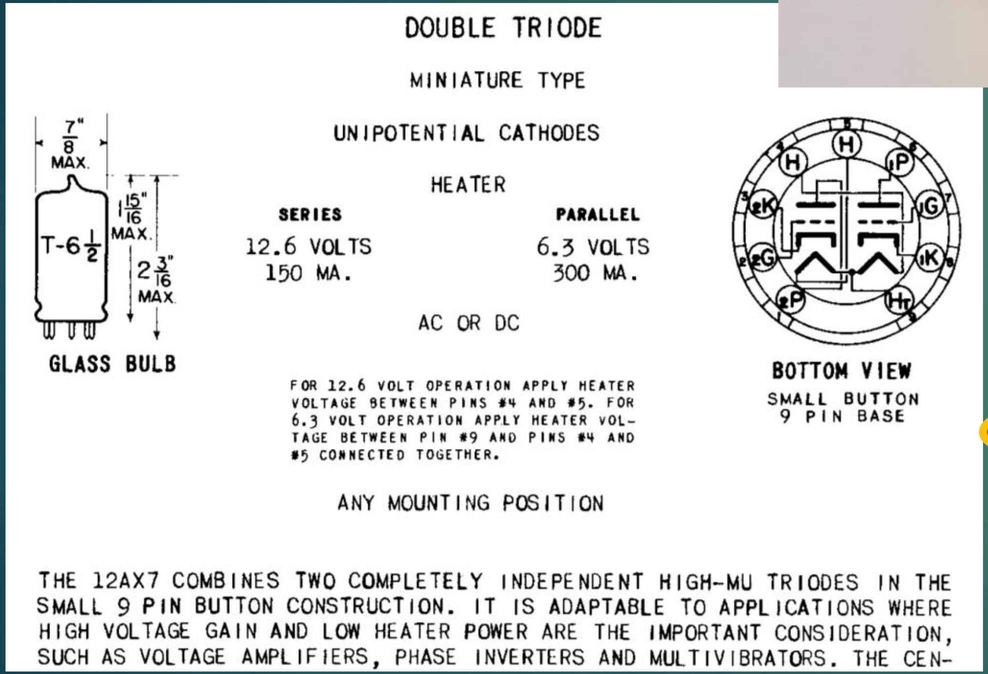
"*Transconductance*"

Tube-based RF Amplifier



$$A_v = -g_m\,\mathrm{R} \quad @\ f_o$$

Transconductance Values


DOUBLE TRIODE

MINIATURE TYPE

UNIPOTENTIAL CATHODES

HEATER

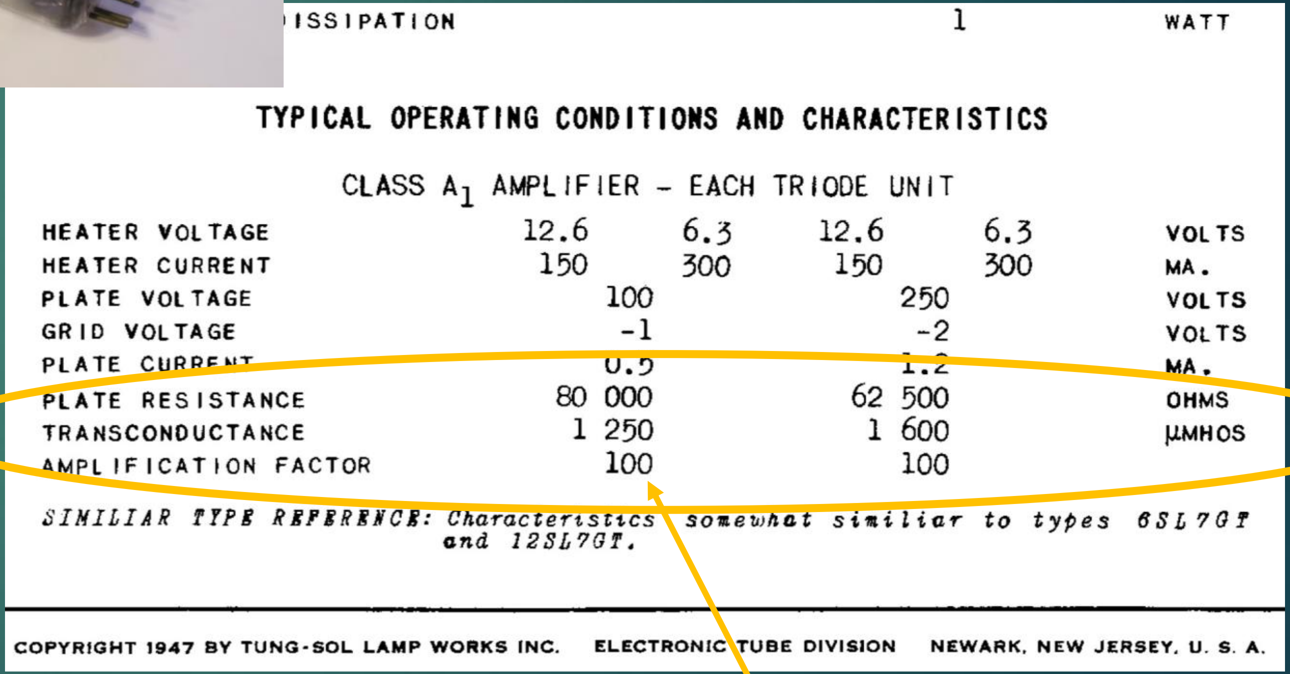
SERIES	PARALLEL
12.6 VOLTS	6.3 VOLTS
150 MA.	300 MA.

AC OR DC

FOR 12.6 VOLT OPERATION APPLY HEATER VOLTAGE BETWEEN PINS #4 AND #5. FOR 6.3 VOLT OPERATION APPLY HEATER VOLTAGE BETWEEN PIN #9 AND PINS #4 AND #5 CONNECTED TOGETHER.

ANY MOUNTING POSITION

THE 12AX7 COMBINES TWO COMPLETELY INDEPENDENT HIGH-MU TRIODES IN THE SMALL 9 PIN BUTTON CONSTRUCTION. IT IS ADAPTABLE TO APPLICATIONS WHERE HIGH VOLTAGE GAIN AND LOW HEATER POWER ARE THE IMPORTANT CONSIDERATION, SUCH AS VOLTAGE AMPLIFIERS, PHASE INVERTERS AND MULTIVIBRATORS. THE CEN-


…ISSIPATION 1 WATT

TYPICAL OPERATING CONDITIONS AND CHARACTERISTICS

CLASS A_1 AMPLIFIER - EACH TRIODE UNIT

HEATER VOLTAGE	12.6	6.3	12.6	6.3	VOLTS
HEATER CURRENT	150	300	150	300	MA.
PLATE VOLTAGE	100		250		VOLTS
GRID VOLTAGE	-1		-2		VOLTS
PLATE CURRENT	0.5		1.2		MA.
PLATE RESISTANCE	80 000		62 500		OHMS
TRANSCONDUCTANCE	1 250		1 600		µMHOS
AMPLIFICATION FACTOR	100		100		

SIMILIAR TYPE REFERENCE: Characteristics somewhat similiar to types 6SL7GT and 12SL7GT.

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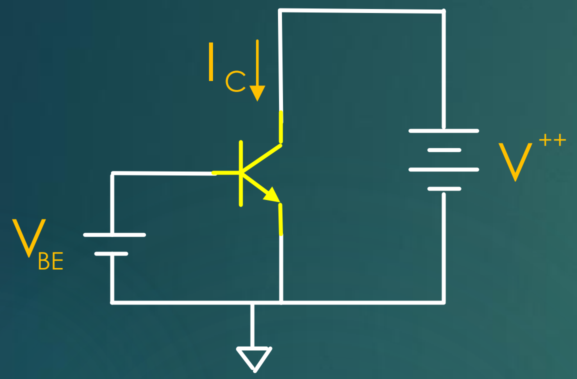
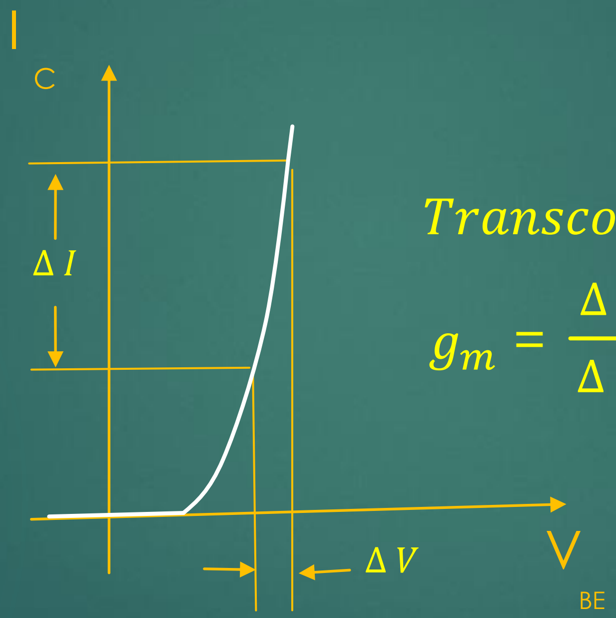
$$A_v = -g_m \, R \; = -(1250 \; x \; 10^{-6})(80{,}000) = -100$$

BJT Transconductance





Transconductance

$$g_m = \frac{\Delta I}{\Delta V}$$

g_m *varies with bias current*

For a BJT device:

$$g_m = \frac{I_c}{nV_T} \approx \frac{I_c}{0.04}$$

Amplifier Design Basics are Device-Independent

(but bias circuits and details vary)

Tube Amp

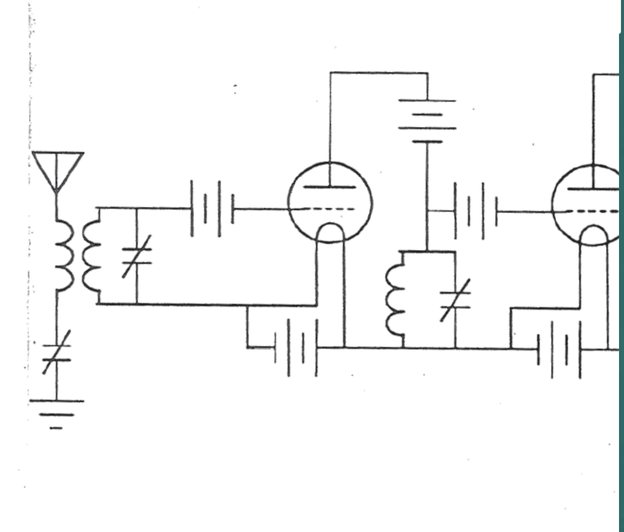
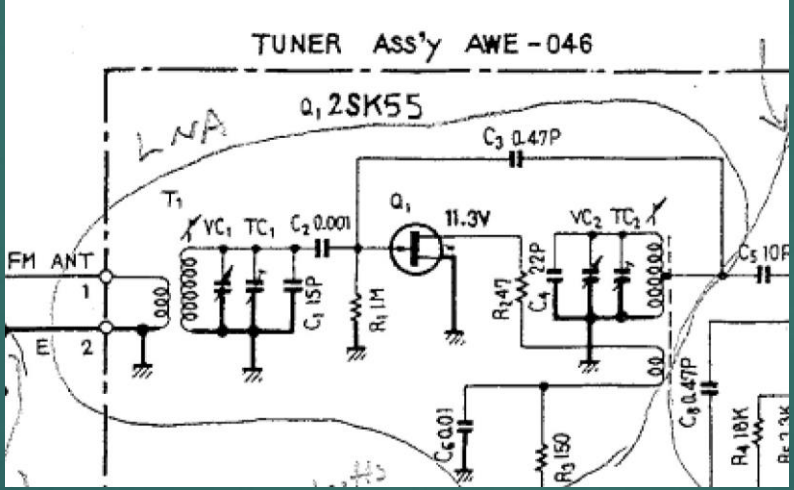
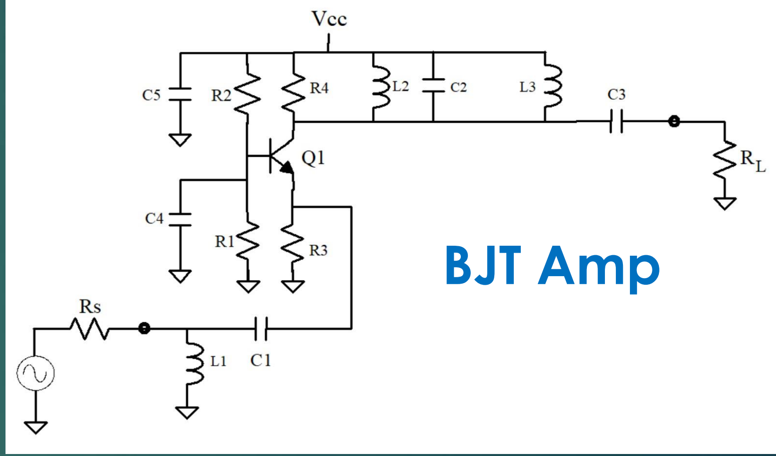


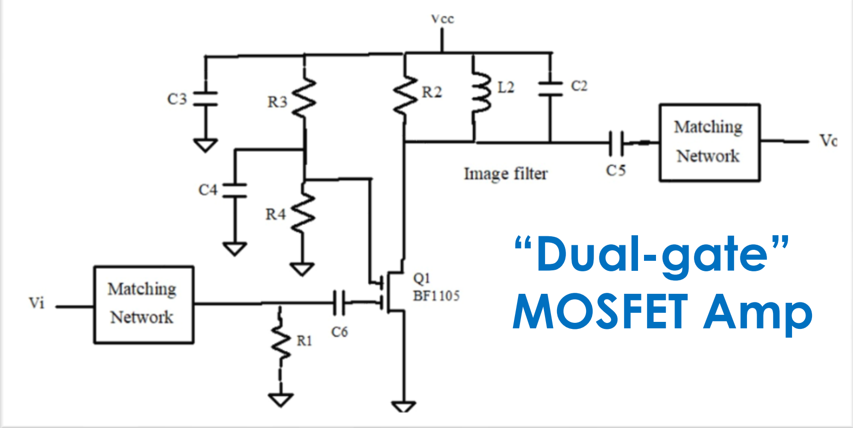
Figure 4.2: Early tuned-RF receiver

JFET Amp





BJT Amp

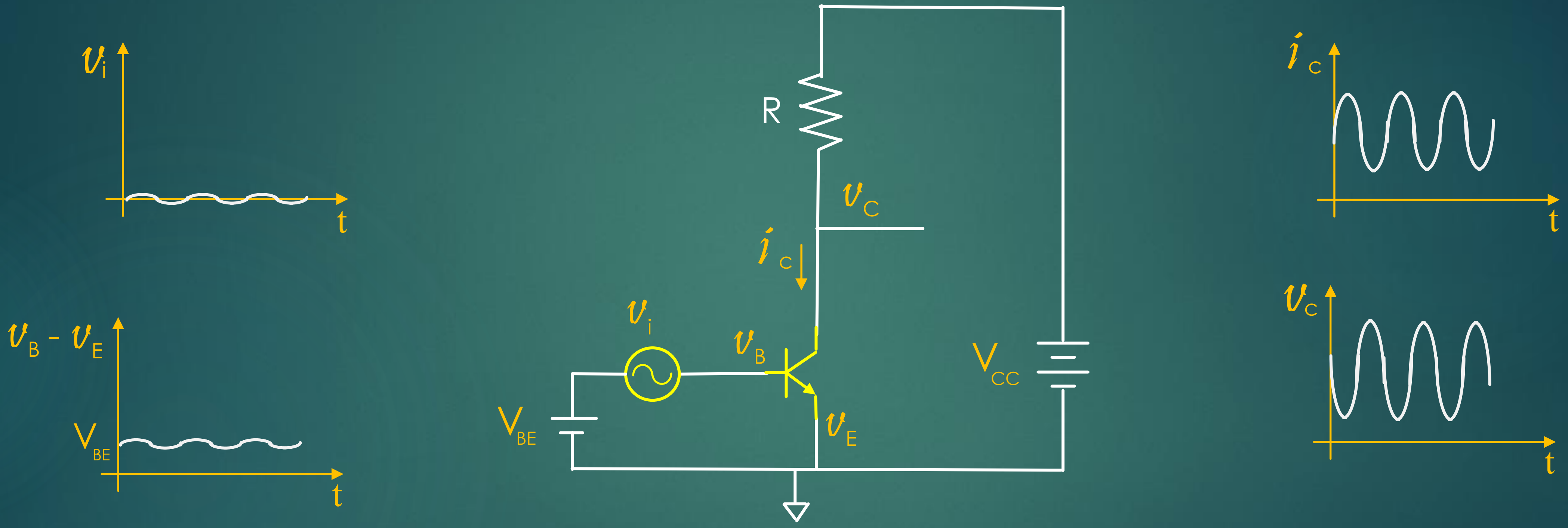


“Dual-gate” MOSFET Amp

Topic Outline

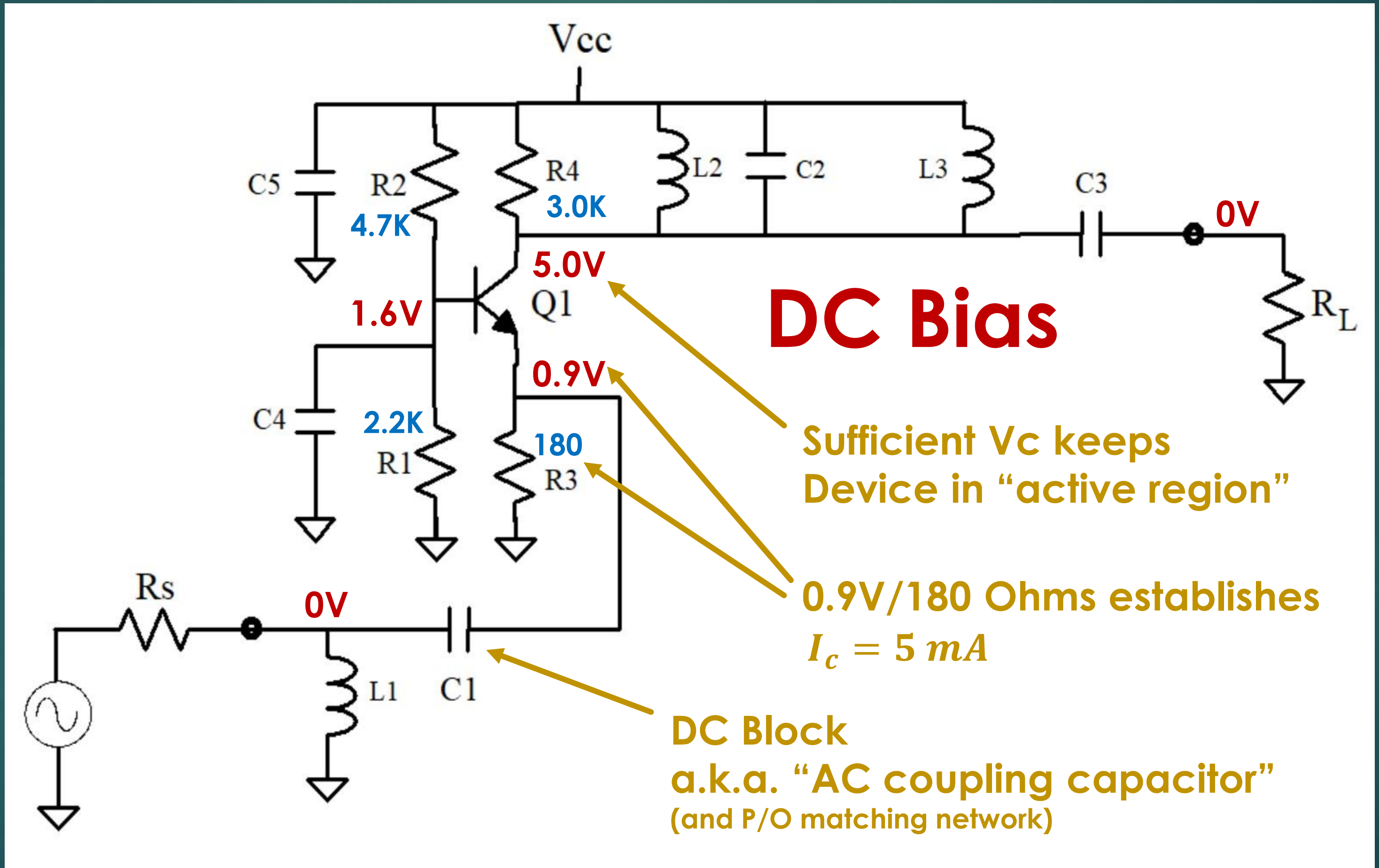
- *Triode Devices*
- ***DC Biasing***
- *AC Gain and I/O Impedances*
- *Amplifier Configurations*
- *High Frequency Limitations*
- *Data Sheets and Example Circuits*

Recall Amplifier Concept



Requires multiple batteries ☹
Bias current is not stable in this circuit ☹
Input source isn't ground referenced ☹

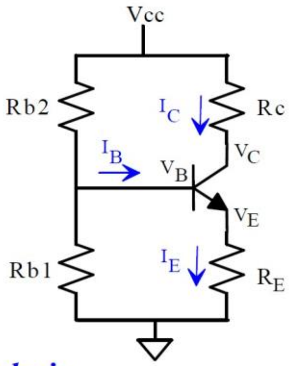
Practical BJT Biasing Circuit



BJT Bias Circuit Analysis

DC Biasing of Class A BJT Amplifiers

A traditional "4-resistor bias circuit" is shown below.



Bias circuit analysis

Assume the transistor is operating in the active region, and that Beta or h_{FE} is "large". Then, I_B will be approximately zero (relative to the current in R_{b1}, R_{b2}), and we can use the simple voltage divider formula at the base to get,

$$V_B \approx V_{cc}\frac{Rb1}{Rb1+Rb2}$$

If the transistor is in the active region, the BE junction is forward biased and $V_{BE_{on}} \approx 0.7V$. Hence,

$$V_E \approx V_B - 0.7$$

The emitter current is then,

$$I_E = \frac{V_E}{R_E}$$

and the collector current is,

$$I_C \approx I_E$$

Finally, the collector voltage can be found from the IR drop in Rc as,

$$V_C = V_{CC} - I_C R_C \;*$$

Note that these equations are reasonably independent of the transistor gain h_{FE} , provided the current through R_{b1} and R_{b2} is >> I_B. Hence, the bias voltages and currents should not change significantly with changes in h_{FE}

Note also that the bias current and DC voltages will be relatively insensitive to small variations in V_{BE} caused by temperature or manufacturing, provided that V_E is greater than about 0.5 to 1 volt.

* For an RF amplifier with LC across Rc, Vc will be equal to Vcc

BJT Bias Circuit Design

Bias Circuit Design

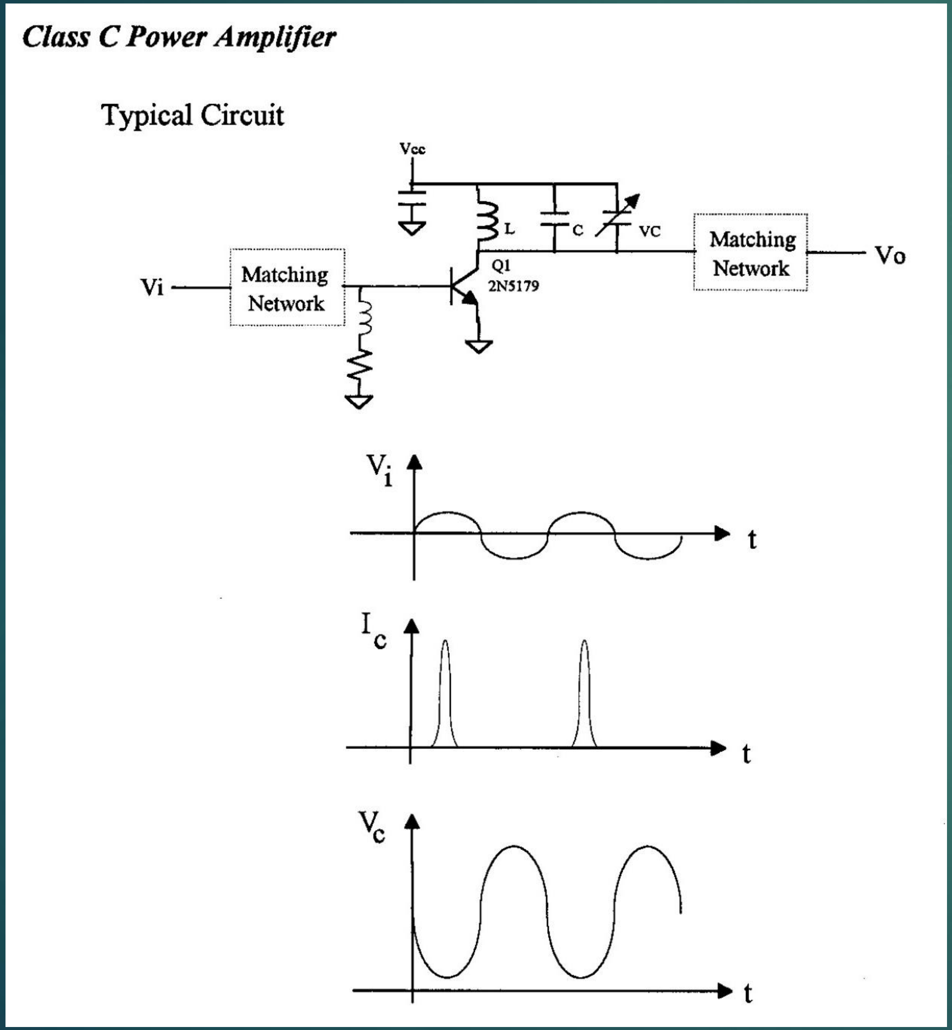
The following procedure is based on the simplified analysis on the previous page.

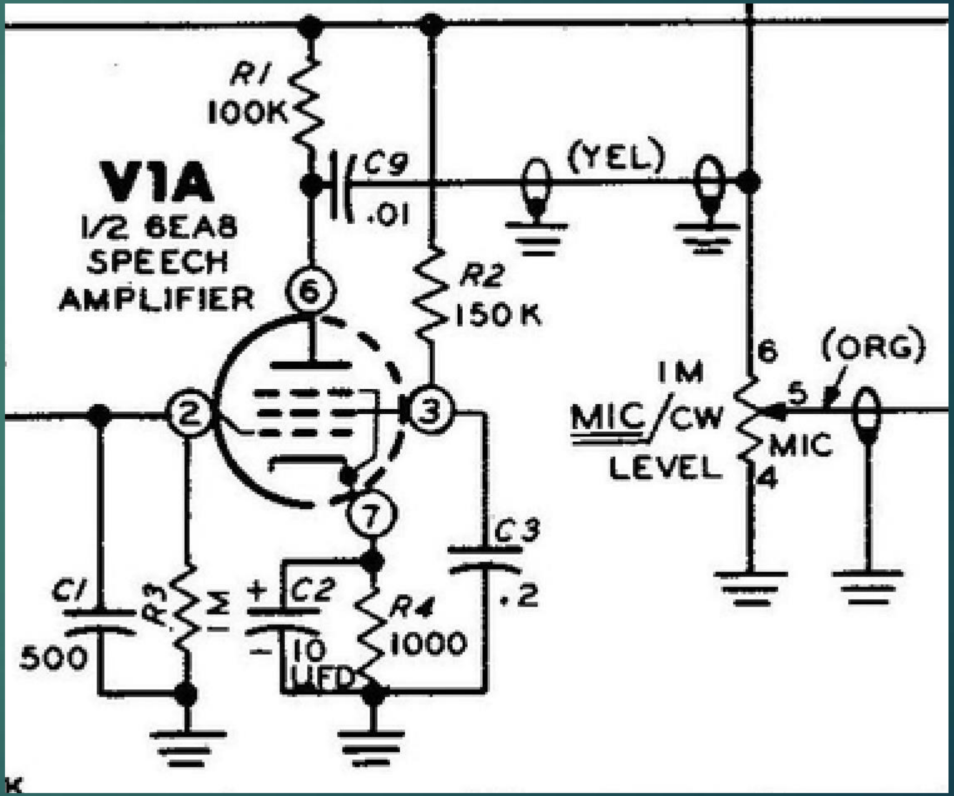
- Pick $V_E > 0.5$ V to swamp V_{BE} variations due to manufacturing and temperature changes. (But not so high that it significantly degrades the output signal swing you can achieve.)
- Pick R_E to give the desired I_E. (Hence the desired I_C since the two are approximately equal).
- Find V_B from $V_B \approx V_E + 0.7$.
- Find I_{Bmax} from I_C and the ***minimum*** transistor h_{FE} value in the datasheet.
- Find R_{b1} and R_{b2} to produce the value of V_B above, subject to the constraint that the current in R_{b1}, R_{b2} is much greater than I_{Bmax}. (Typically 5 to 10 times I_{Bmax} is used, but this could be relaxed some since we're already using the worst-case I_B.)
- Fine-tune R_{b1} and R_{b2} if desired to account for the (small) lowering of V_B due to the non-zero base current expected (use the *typical* h_{FE} here to provide good "design-centering").
- Find R_c to produce a desired V_C and to satisfy other design constraints such as the amplifier gain.
- Convert resistors to available values.
- Check to be sure the transistor is operating comfortably in the active region !!

* *NOTE: For small current circuits, we can stop here, but in general you should consider power dissipations in the transistor and resistors and be sure you don't approach or exceed the limits...*

* For an RF amplifier with LC across Rc, Vc can reach 2 xVcc, so need to check V_{CE} breakdown spec also

Some Additional Bias Circuits

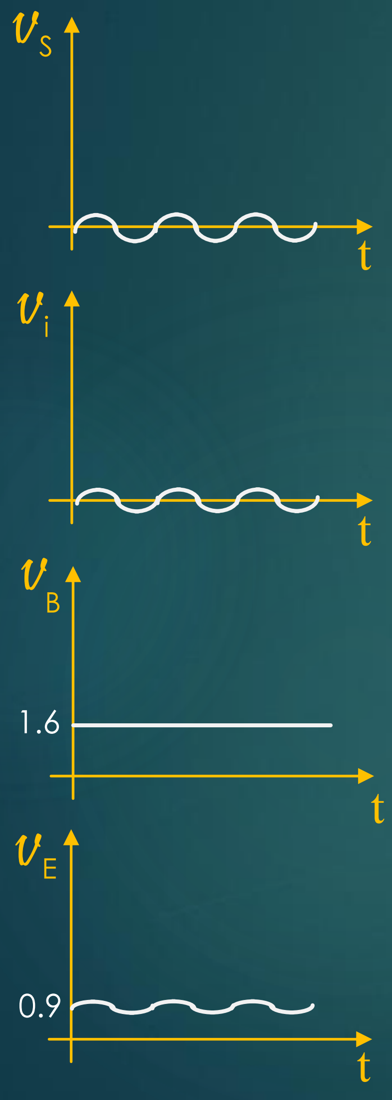


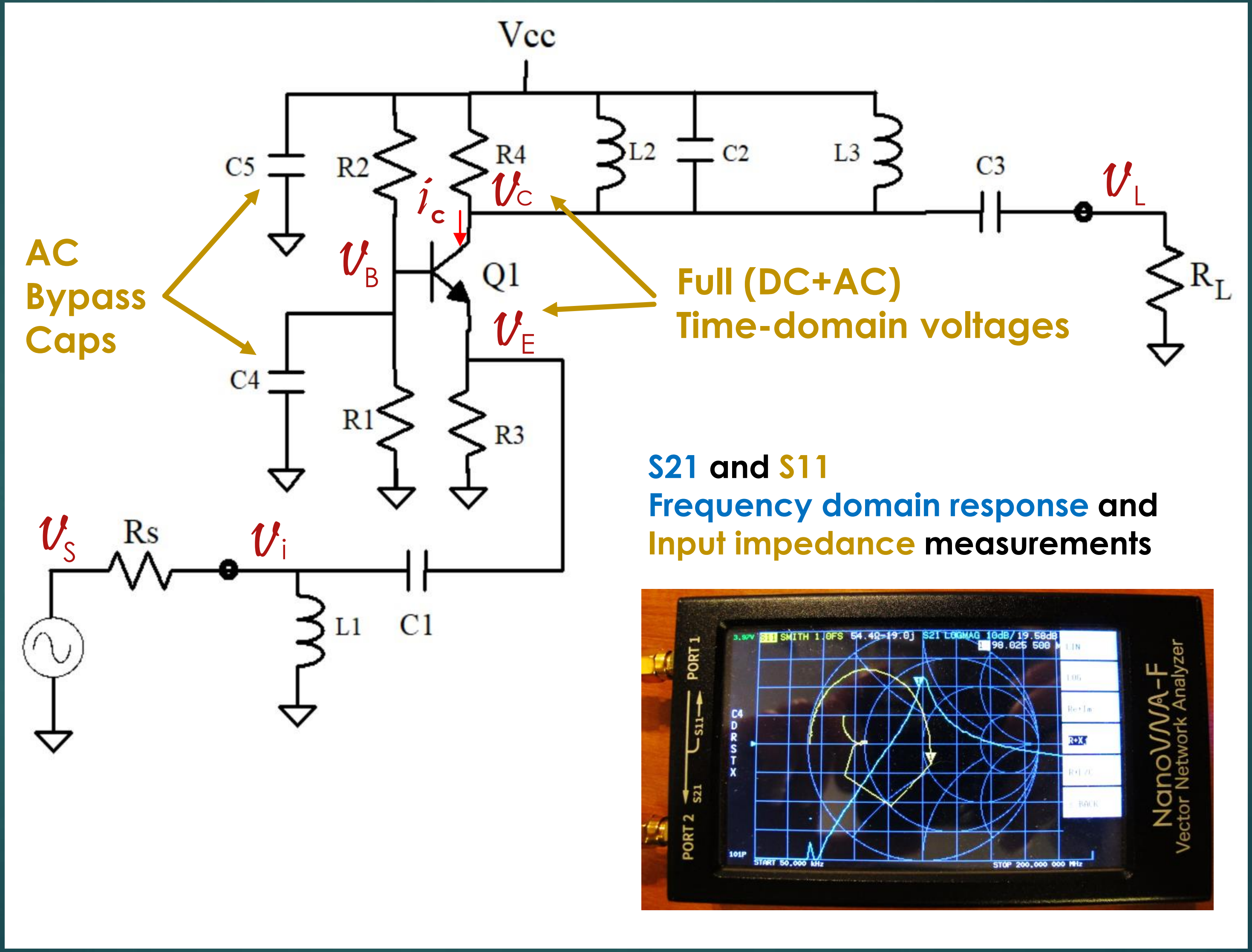


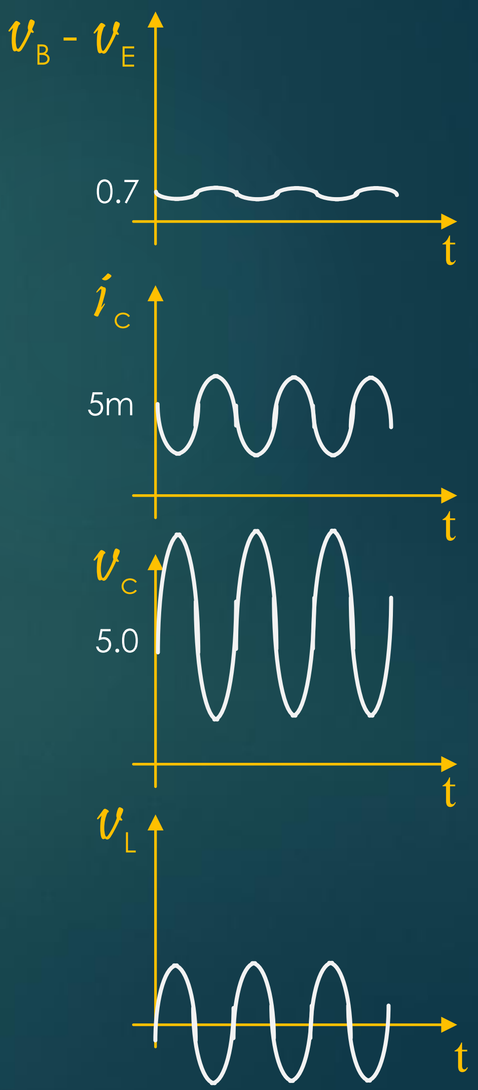
Topic Outline

- *Triode Devices*
- *DC Biasing*
- ***AC Gain and I/O Impedances***
- *Amplifier Configurations*
- *High Frequency Limitations*
- *Data Sheets and Example Circuits*

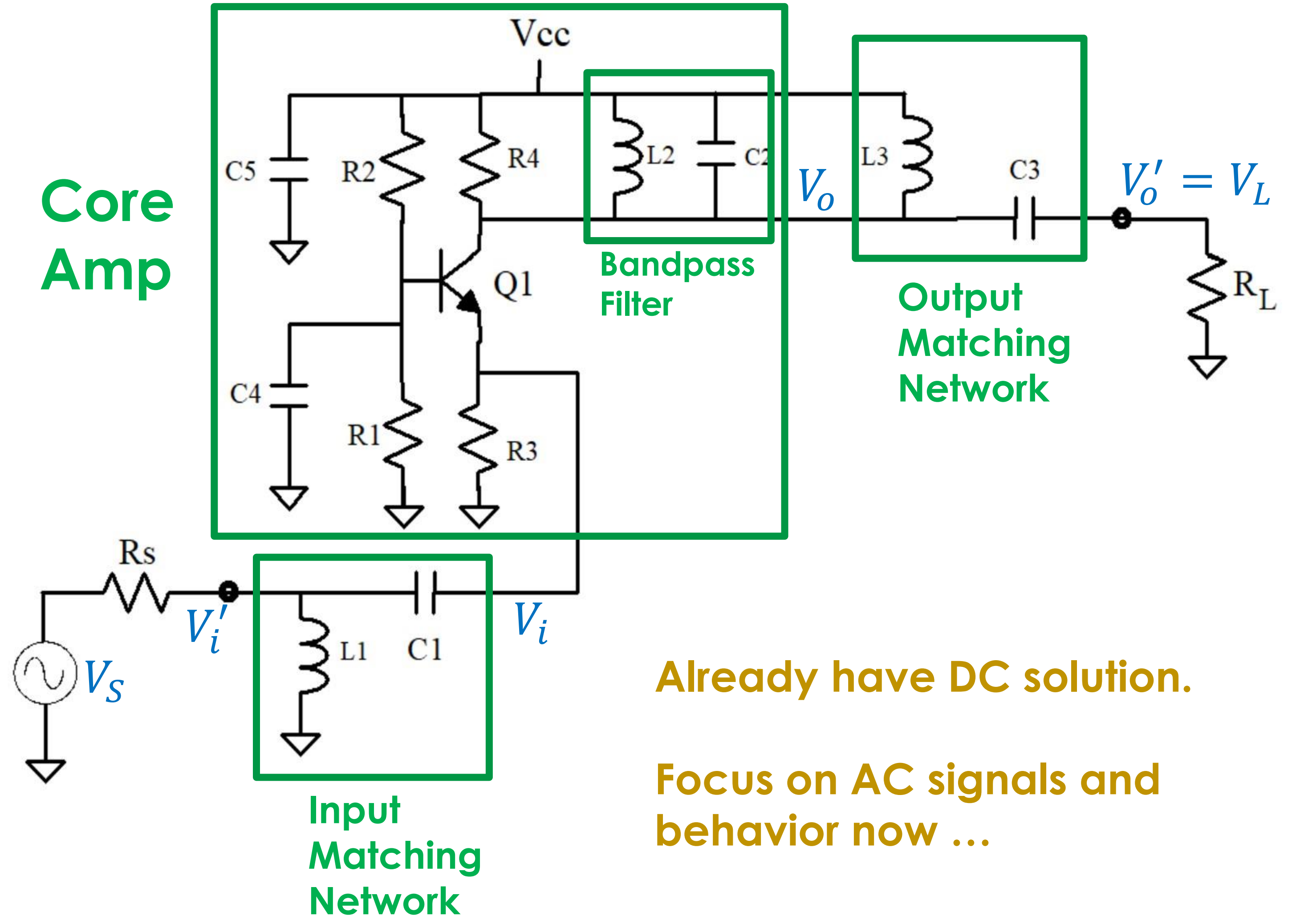
Full Circuit Behavior







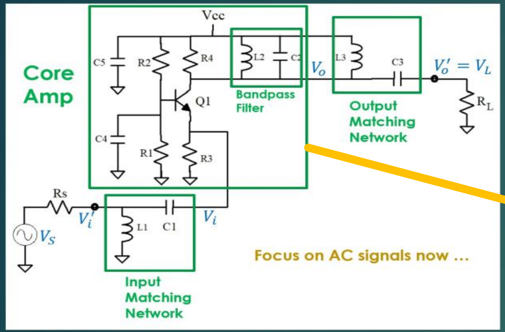
Circuit Understanding



Already have DC solution.

Focus on AC signals and behavior now …

Core Amp AC Small Signal Model



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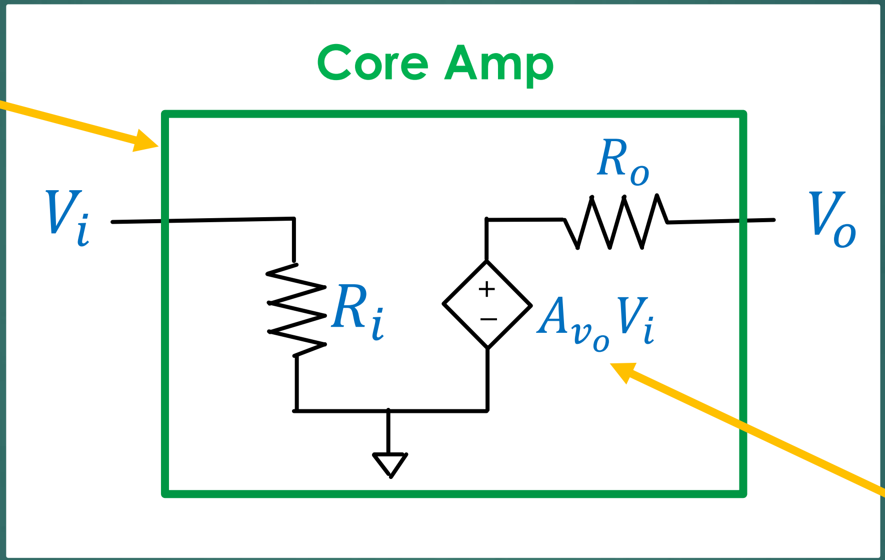


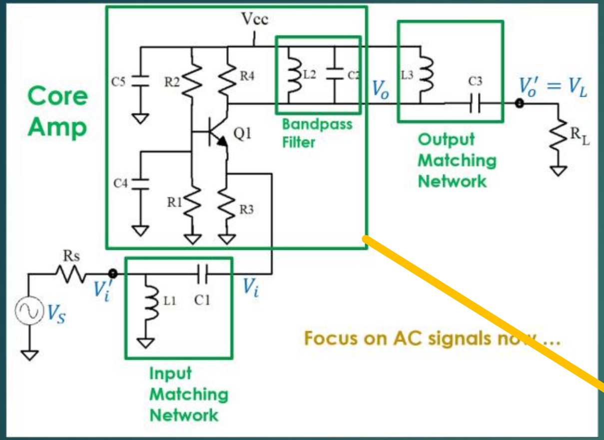
Simplified ***equivalent circuit*** of Core Amp (@ fo)

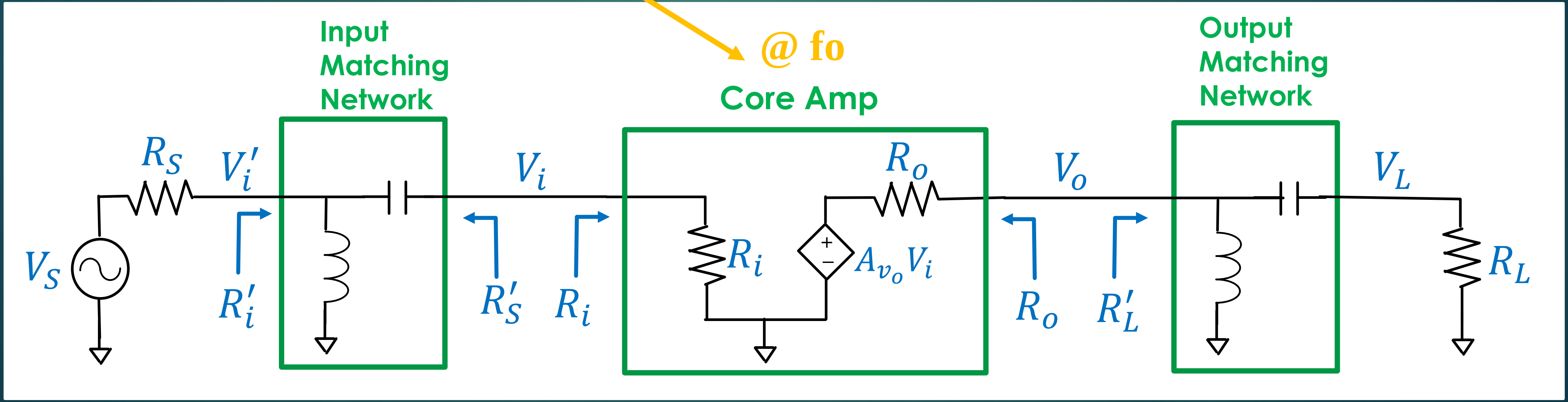
Based on Thevenin's theorem and linear systems theory

$A_{v_o} = \frac{V_o}{V_i}$ *with no loading*

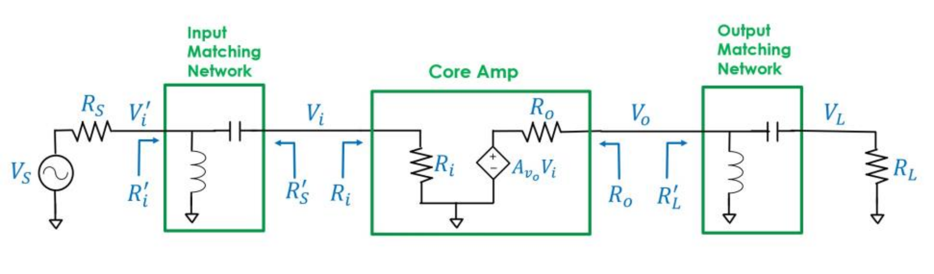
- Ri, Ro, and Avo depend on amplifier device, circuit configuration, and biasing
- In general, we should use Zi, Zo, and complex frequency-dependent gain, but this simplified treatment is sufficient for this particular Radio 101 video…

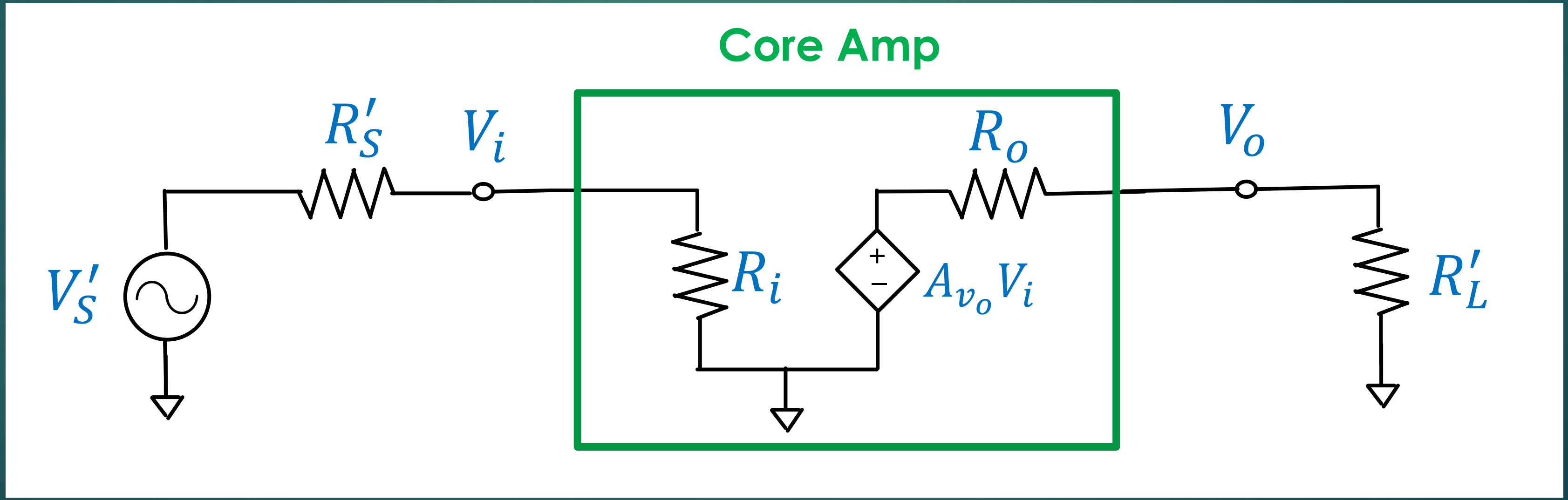
Using the Model





Concentrating on the Core





Knowing Ri, Avo, and Ro is critical to:

- Interfacing with source and load
- Calculating voltage division factors
- Matching for maximum power gain
- **Understanding analog/RF circuits !**

Overview of Part 2

- *Triode Devices*
- *DC Biasing*
- *AC Gain and I/O Impedances*
- ***Amplifier Configurations***
- ***High Frequency Limitations***
- ***Data Sheets and More Example Circuits***

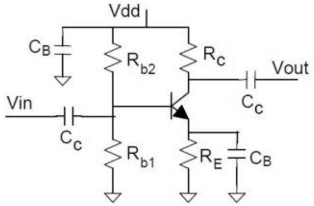
Part 2

Amplifier Configurations Preview

BJT Amplifier Configurations

Configuration	Representative Circuit	Approx. Formulas	$A_{Vno\text{-}load}$	R_i	R_o

Common Emitter

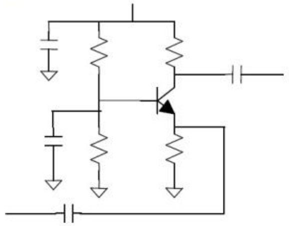


$A_{Vno\text{-}load} = -\, g_m\, (R_c||r_o)$ — High, Med, Med

$R_i = r_\pi \;||\; R_{b1} \;||\; R_{b2}$
where $r_\pi = h_{fe}/g_m$

$R_0 = R_c \;||\; r_o$

Common Base

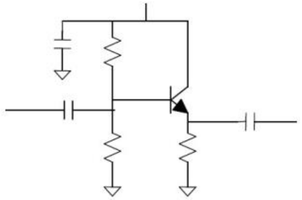


$A_{Vno\text{-}load} = +g_m\, (R_c||r_o)$ — High, Low, Med

$R_i = 1/g_m \;||\; R_E \;||\; r_\pi$

$R_o = R_c \;||\; r_o$

Common Collector (Emitter follower)



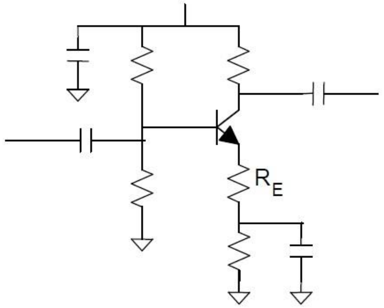
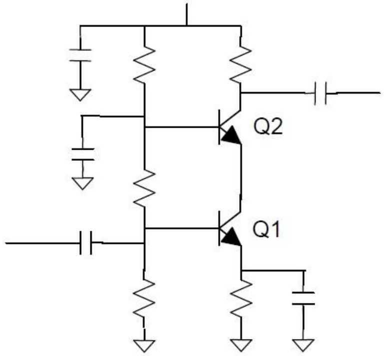
$A_{Vno\text{-}load} \approx 1$ — Unity, High, Low

$R_i = R_{b1} \;||\; R_{b2} \;||\; r_\pi(1+g_m R_E)$*

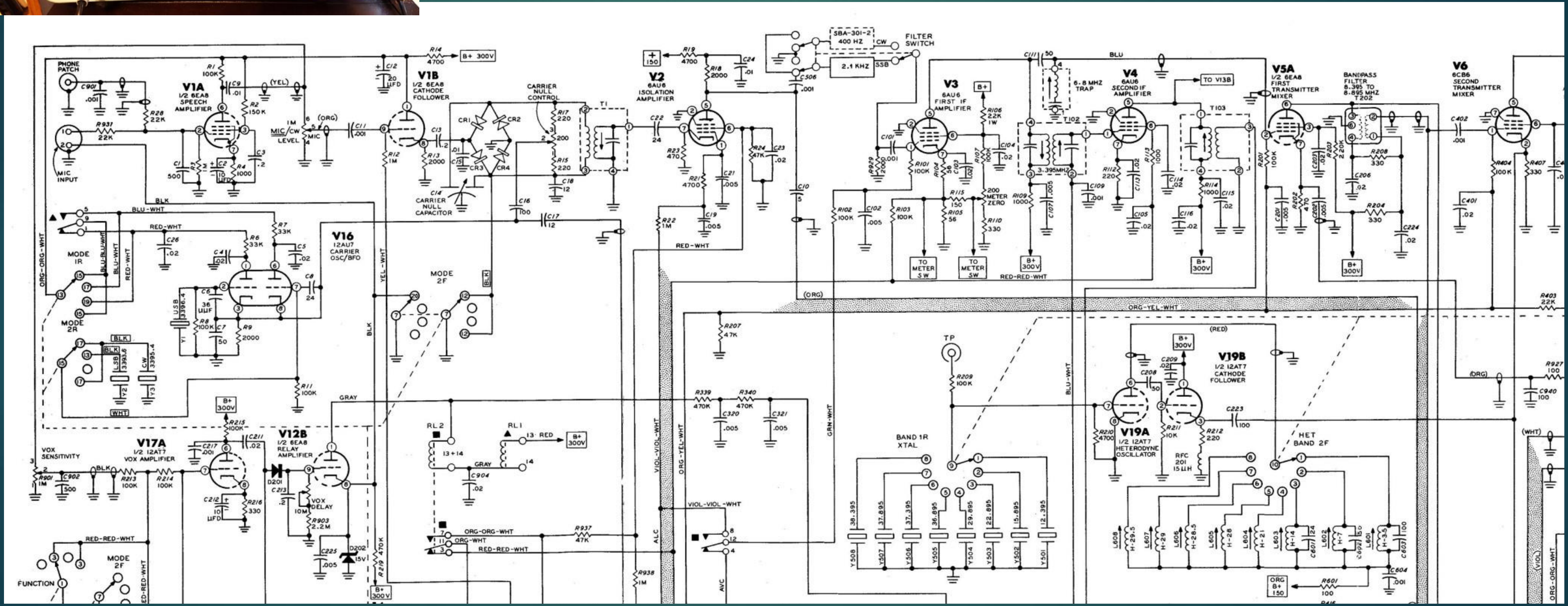
$R_o = 1/g_m$**

* Assumes unloaded output
** Assumes low source R

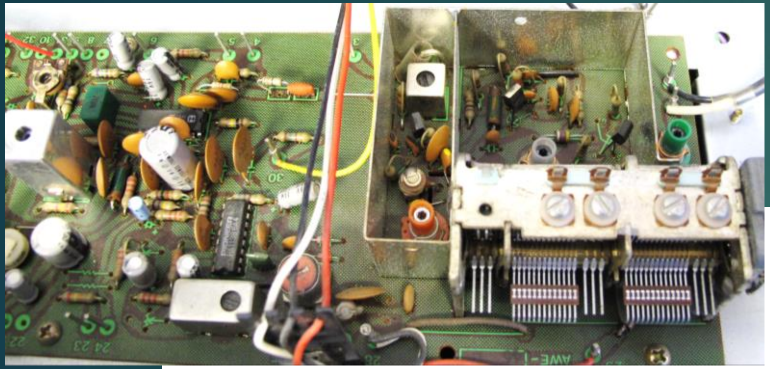
Amplifier Configurations Preview

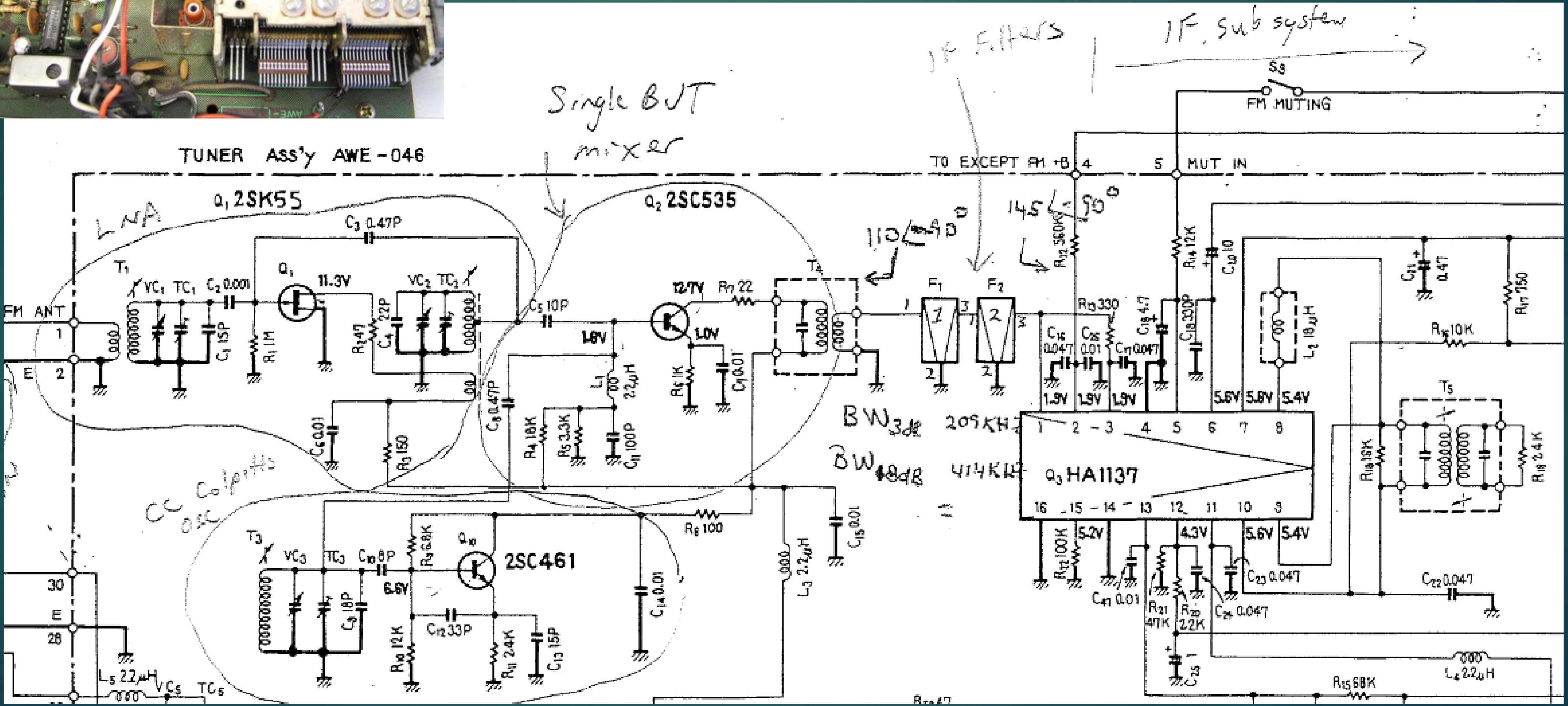
Configuration	Representative Circuit	Approx. Formulas	$A_{Vno\text{-}load}$	R_i	R_o
Common Emitter with Emitter Resistor		$A_{Vno\text{-}load} = -g_m R_c / (1+g_m R_E)$ $R_i = R_{b1} \parallel R_{b2} \parallel r_\pi(1+g_m R_E)$ $R_0 = R_c \parallel r_o$	Med	High	Med
Cascode (CE + CB)		$A_{Vno\text{-}load} = -g_m R_c$ $R_i = R_{b1} \parallel R_{b2} \parallel r_\pi$ $R_0 = R_c \parallel (r_{o1}+r_{o2}(1+g_m r_{o1}))$	High	Med	Med/High

Example Circuit 1



Example Circuit 2





Example Circuit 3

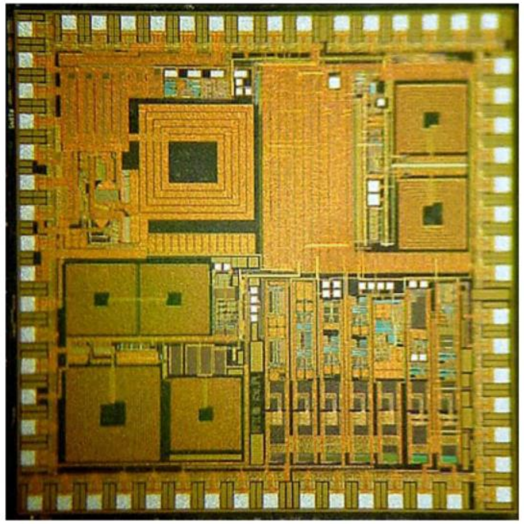


Fig. 39. *Die photo of fully integrated single-chip 100-mW transceiver.*

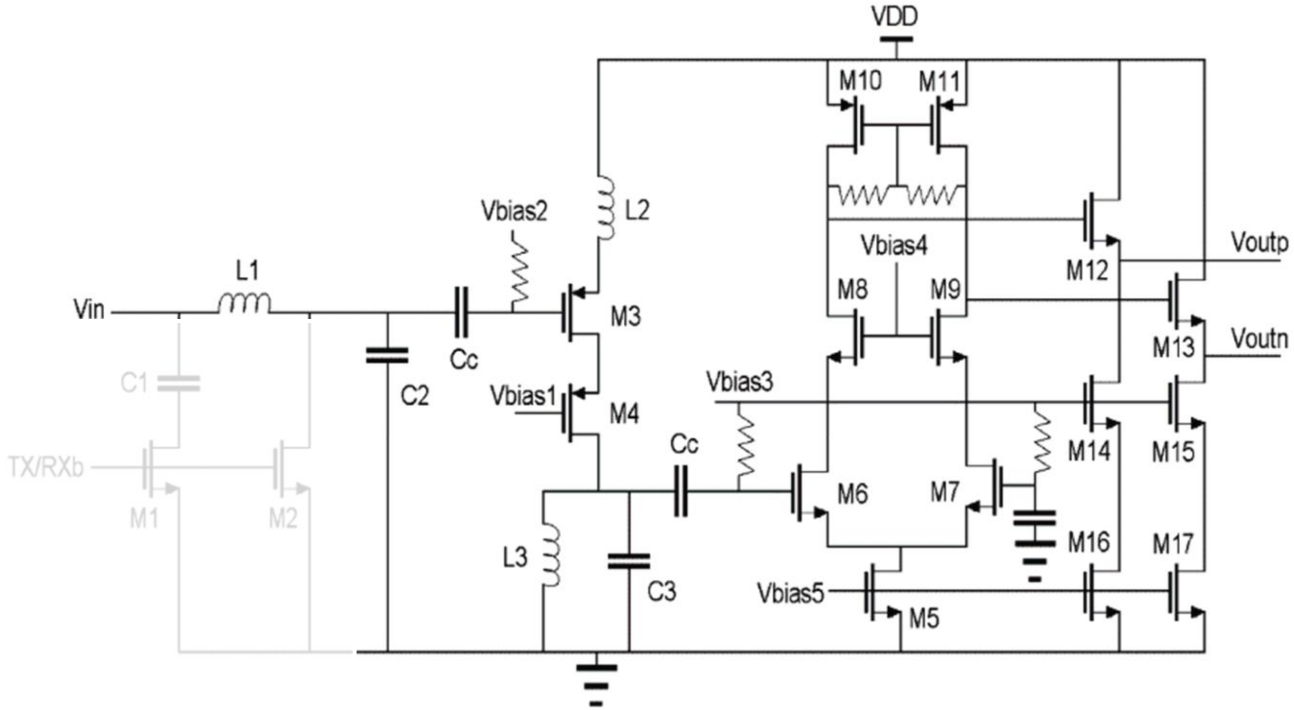
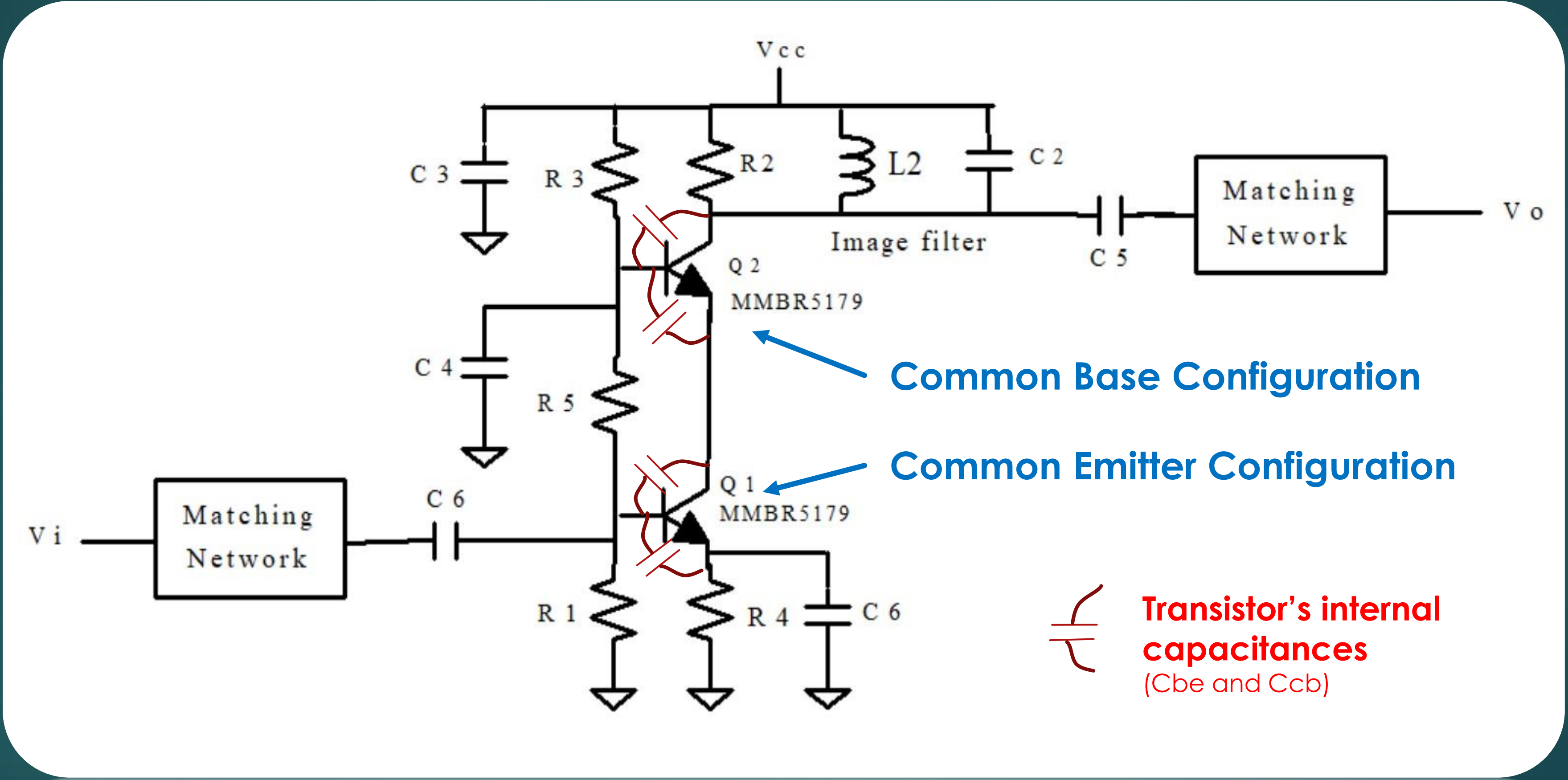


Fig. 23. *Schematic diagram of LNA with integrated T/R switch circuits.*

High-Frequency Behavior

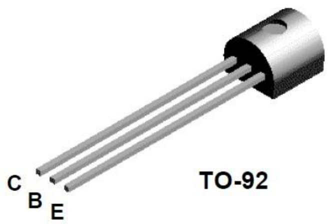


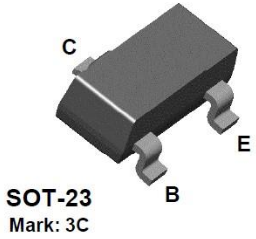
Example Datasheet

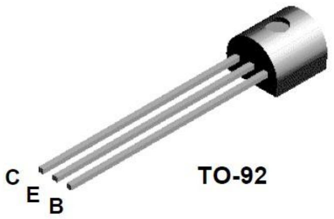
FAIRCHILD
SEMICONDUCTOR ™

MPS5179 / MMBT5179 / PN5179

MPS5179 | MMBT5179 | PN5179







NPN RF Transistor

This device is designed for use in low noise UHF/VHF amplifiers with collector currents in the 100 µA to 30 mA range in common emitter or common base mode of operation, and in low frequency drift, high ouput UHF oscillators. Sourced from Process 40.

Absolute Maximum Ratings*

TA = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CEO}	Collector-Emitter Voltage	12	V
V_{CBO}	Collector-Base Voltage	20	V
V_{EBO}	Emitter-Base Voltage	2.5	V
I_C	Collector Current - Continuous	50	mA

Tabular Data

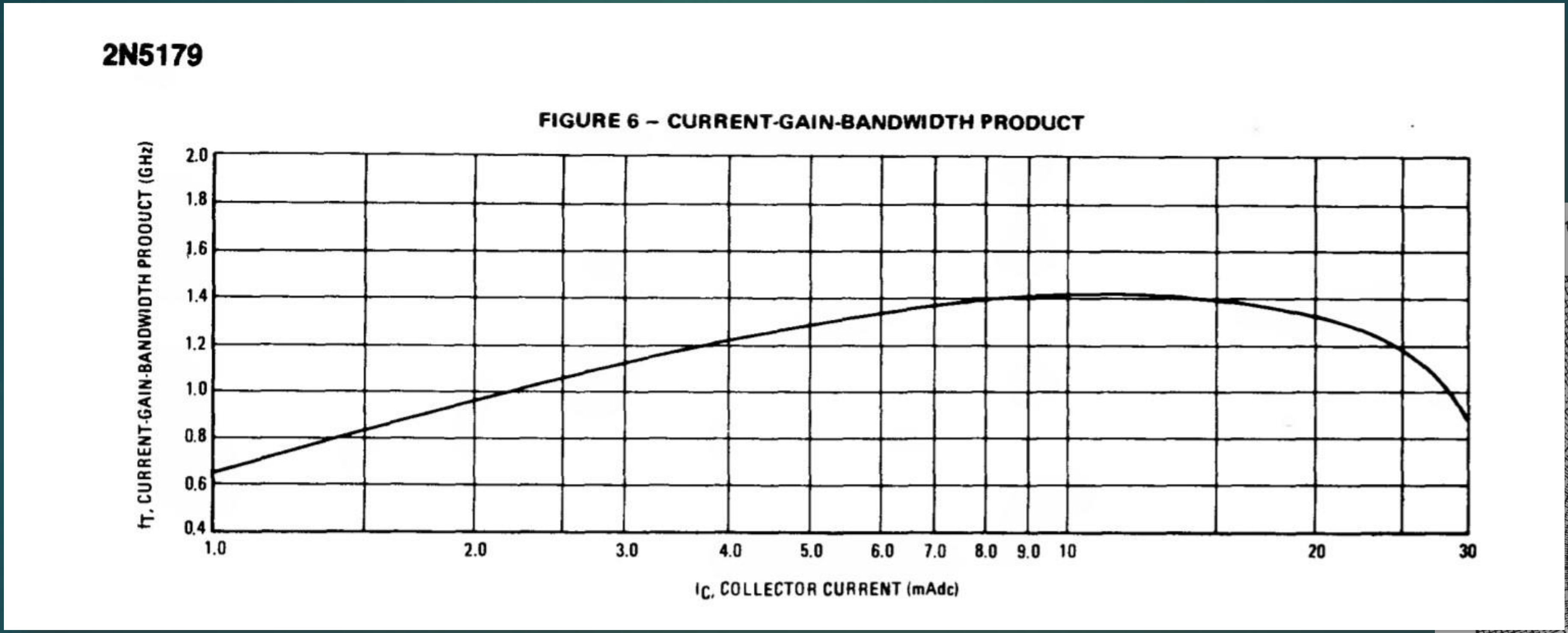
MPS5179 / MMBT5179 / PN5179

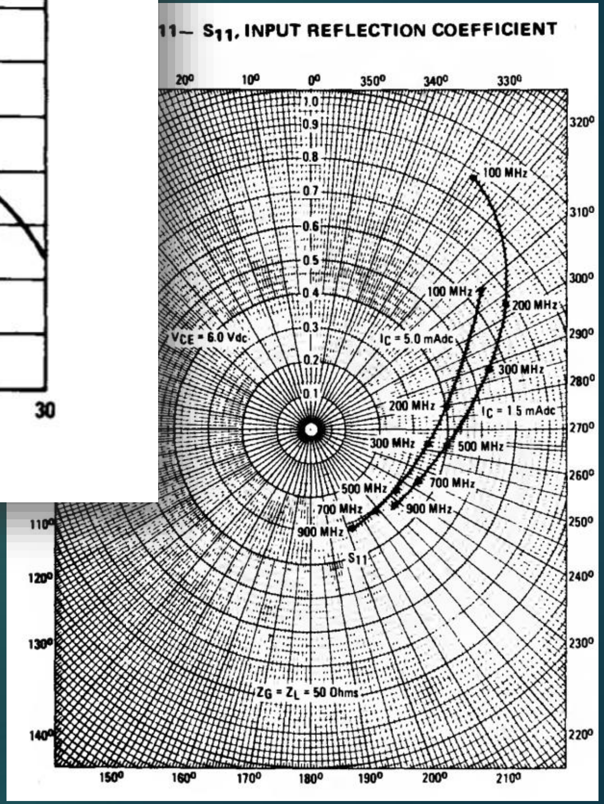
NPN RF Transistor
(continued)

Electrical Characteristics TA = 25°C unless otherwise noted

Symbol	Parameter	Test Conditions	Min	Max	Units
OFF CHARACTERISTICS					
$V_{CEO(sus)}$	Collector-Emitter Sustaining Voltage*	I_C = 3.0 mA, I_B = 0	12		V
$V_{(BR)CBO}$	Collector-Base Breakdown Voltage	I_C = 1.0 μA, I_E = 0	20		V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage	I_E = 10 μA, I_C = 0	2.5		V
I_{CBO}	Collector Cutoff Current	V_{CB} = 15 V, I_E = 0 V_{CB} = 15 V, T_A = 150°C		0.02 1.0	μA μA
ON CHARACTERISTICS					
h_{FE}	DC Current Gain	I_C = 3.0 mA, V_{CE} = 1.0 V	25	250	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	I_C = 10 mA, I_B = 1.0 mA		0.4	V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage	I_C = 10 mA, I_B = 1.0 mA		1.0	V
SMALL SIGNAL CHARACTERISTICS					
f_T	Current Gain - Bandwidth Product	I_C = 5.0 mA, V_{CE} = 6.0 V, f = 100 MHz	900	2000	MHz
C_{cb}	Collector-Base Capacitance	V_{CB} = 10 V, I_E = 0, f = 0.1 to 1.0 MHz		1.0	pF
h_{fe}	Small-Signal Current Gain	I_C = 2.0 mA, V_{CE} = 6.0 V, f = 1.0 kHz	25	300	
$rb'C_c$	Collector Base Time Constant	I_C = 2.0 mA, V_{CB} = 6.0 V, f = 31.9 MHz	3.0	14	ps
NF	Noise Figure	I_C = 1.5 mA, V_{CE} = 6.0 V, R_S = 50Ω, f = 200 MHz		5.0	dB
FUNCTIONAL TEST					
G_{pe}	Amplifier Power Gain	V_{CE} = 6.0 V, I_C = 5.0 mA, f = 200 MHz	15		dB
P_O	Power Output	V_{CB} = 10 V, I_E = 12 mA, f ≥ 500 MHz	20		mW

Graphs and Formulas





$$C_{be} \approx \frac{1}{2\pi \frac{1}{g_m} f_T} - C_{cb}$$

$$r_\pi = \frac{1}{g_m} h_{fe}$$

$$g_m = \frac{I_c}{nV_T}$$

Thanks For Watching !