Modular System RF Design*

"Build Your Own Small Radar System..."
2011 MIT Independent Activities Period (IAP)

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Outline

- Introduction
- Circuit and Network Theory
- RF Measurements
- RF Design/Build
- Summary

RF Design Requirements

Design Parameters

- Frequency = 2.4GHz
- BW = 80MHz
- Waveform = CW Ramp
- Antenna Isolation = 50dB
- DC Power < 1 Watt
- RF Power < 1 Watt (EIRP)

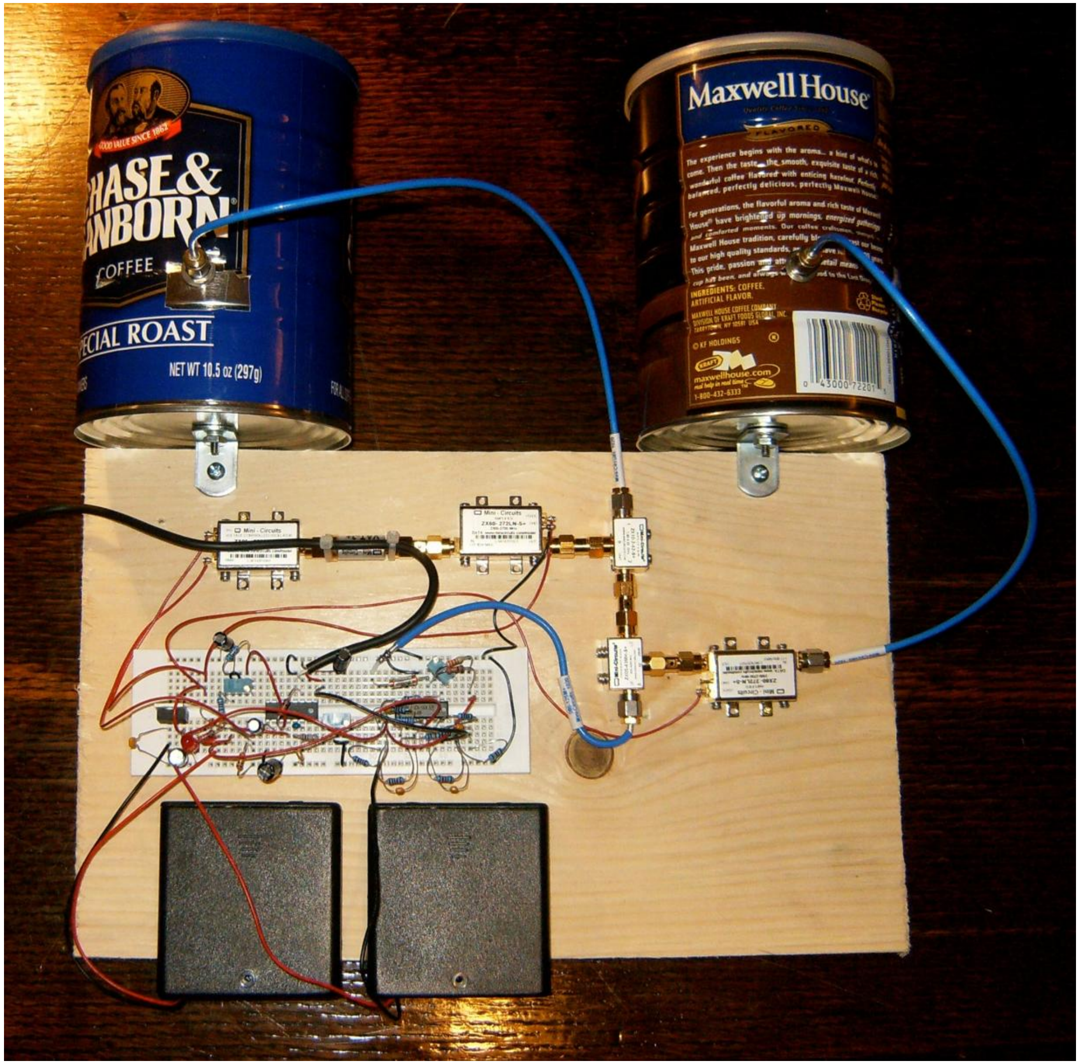
Realization Constraints

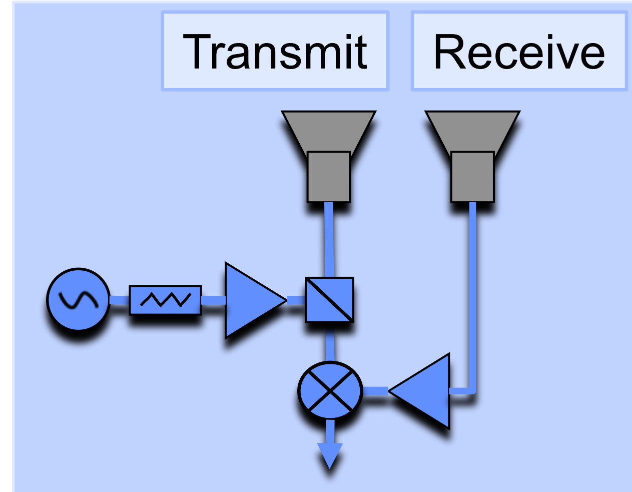
- Use off the shelf parts
- Use connectorized components
- Minimal soldering
- Use AA batteries

Functional Decomposition

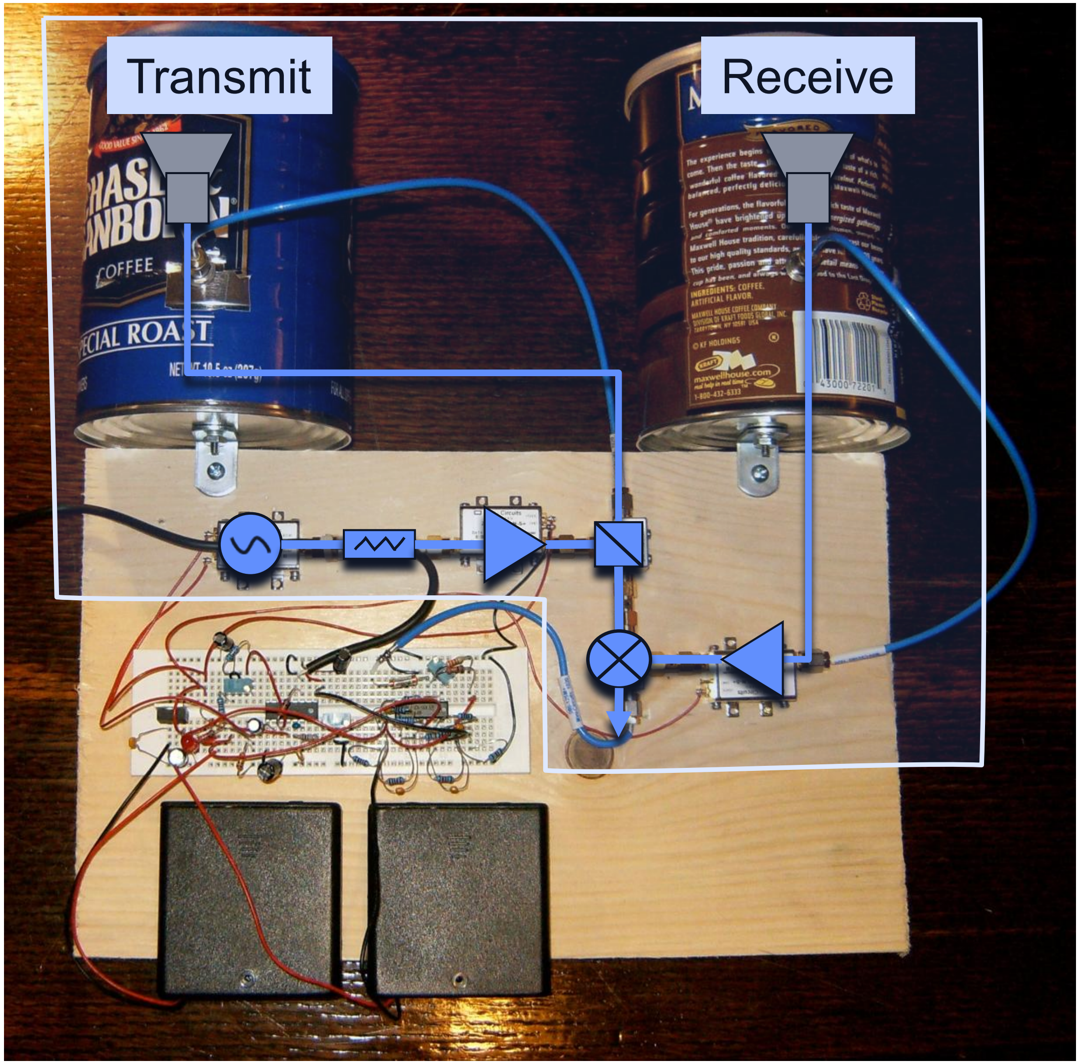
- Transmitter
  - Modulated source
  - Amplification
  - Distribution
  - Antenna for radiation
- Receiver
  - Antenna receive aperture
  - Amplification
  - De-modulate
  - Frequency Translate

Radar RF Components





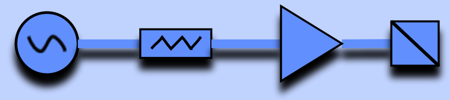
Radar RF Components



Radar RF Components and Models

RF Component Chain

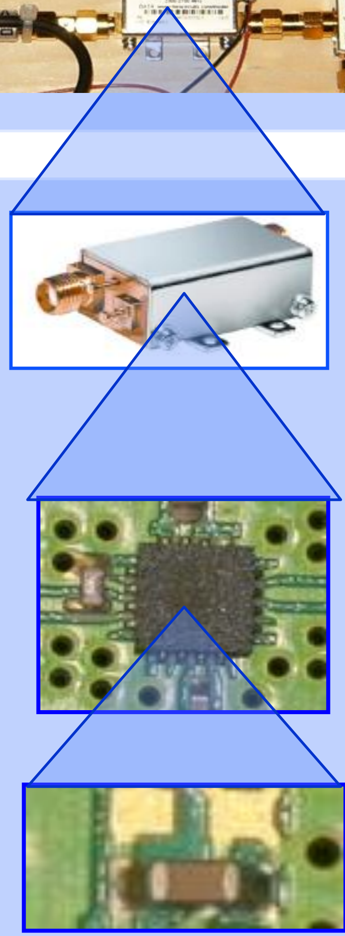
Cascaded Two-Port Network Model

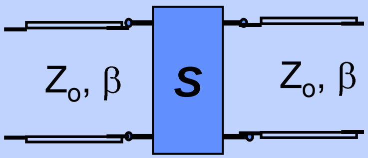


Connectorized Component

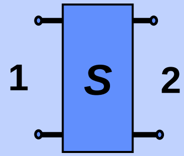
Packaged IC

Chip Capacitor

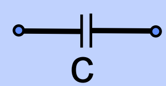




Two-Port with Transmission lines



Two Port RF Component

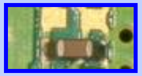


Circuit

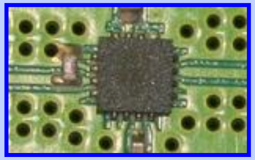
RF Component Shapes and Sizes

- **Devices**
  - Bare Die
  - Monolithic chips
  - Exposed metal for connection
- **Interconnects**
  - Conforms to a standard
  - High density
  - Reliable and easy to use / re-use
- **Packaging**
  - Protection from environment
    - RF radiation, chemical, hermetic…
  - Thermal flow
  - Mechanical structure

Bare chip



Packaged
Integrated circuit



Connectorized packaging

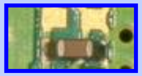
Components are characterized at their terminal pairs

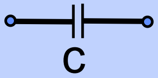
Circuit and RF Component Models

- **Circuit components**
  - Component behavior is described at the terminals
  - Using a current-voltage relationship
  - Components are connected with <u>ideal lines</u> to form a circuit
  - Circuit theory used to determine overall circuit behavior

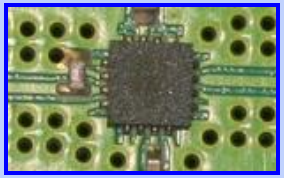
- **RF components**
  - Component behavior is described at terminal pair <u>ports</u>
  - Using <u>scattering parameters</u>
  - Components are connected by <u>transmission lines</u>
  - Network theory used to determine overall behavior

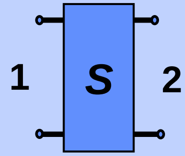
Circuit Model



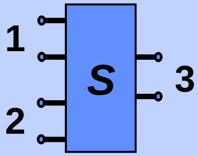


Two Port Network Model





3 Port Network Model



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- RF Measurements
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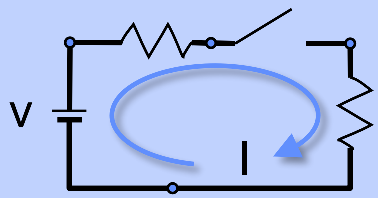
Circuit and Network Theory

- **The circuit model**
  - A circuit describes how energy is guided through interconnected components
  - Circuits vary in one dimension along a path, not in 3D like fields
  - Component effects are lumped into a point along the circuit (size doesn't matter)

Flash light circuit



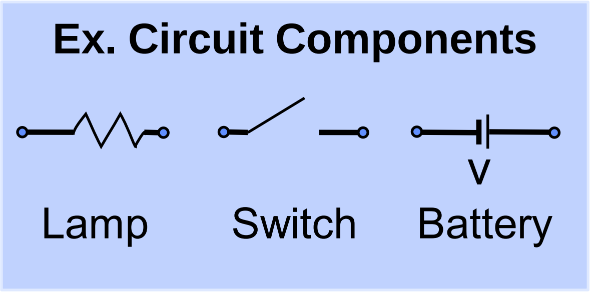
- **Use circuit theory to write and solve network equations**
  - Ohms law
  - Kirchhoff's laws
  - Norton's theorem
  - Superposition theorem
  - Duality

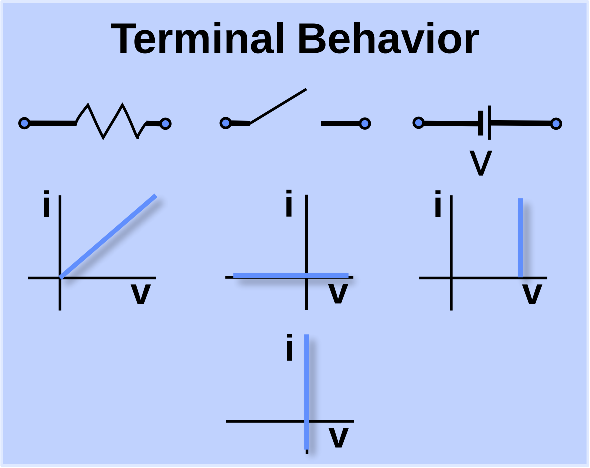
Overall circuit behavior is determined by solving network equations

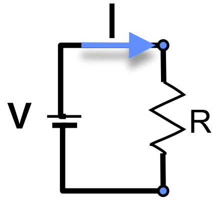
Circuit Component Terminal Behavior

- **Terminal behavior of a resistor**
  - **Voltage and current vary together such that their ratio is a constant**

    R = V/I
  - **Voltage in volts, current in amps gives resistance in ohms (Ohm's Law)**
- **Experimental general solution**
  - **Measure the current-voltage relationship at the terminals**
  - **Directly connect a voltage or current source as the free parameter**
  - **measure the dependent parameter**
- **Analytic general solution**
  - **Given full 3D geometry of the component**
  - **Solve for electromagnetic (EM) fields**
  - **Determine current-voltage relationship at the terminals**

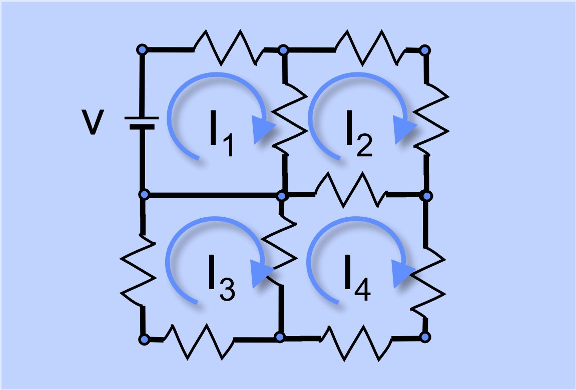


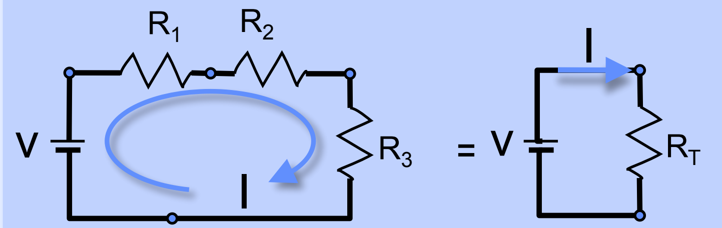




Circuit Theory – Kirchhoff's Laws

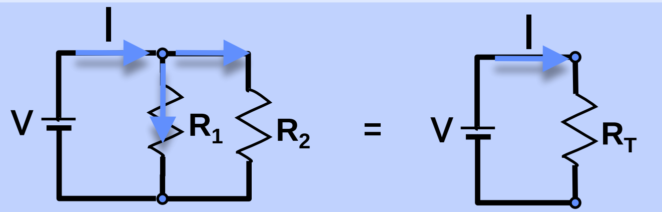
- **Kirchhoff's voltage law: sum of voltages around any closed loop is zero**
- **Kirchhoff's current law: sum of currents into any node is zero**
- **In general N equations for N loops or nodes**





Series circuit – common current

$R_T = R_1 + R_2 + R_3$



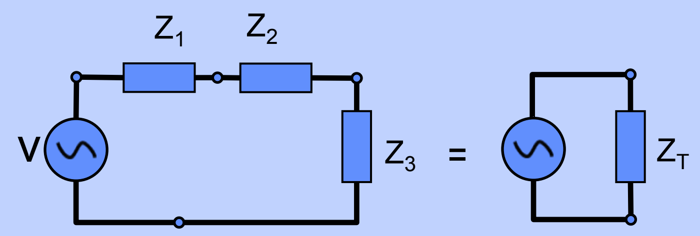
Parallel circuit – common voltage

$R_T = R_1R_2 /(R_1+R_2)$

Use linear algebra to solve for circuit behavior

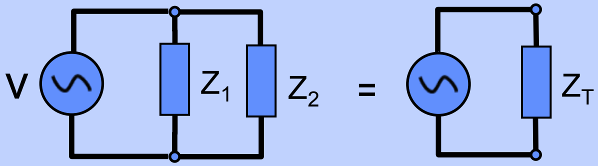
Circuit Theory – Impedance

- **Given excitations are exponential functions of time**
  - $v = V e^{st}$
  - $i = I e^{st}$
- **Impedance is the ratio of voltage to current**
  - $Z = v/i$ **in ohms**
- **We can now model resistors, capacitors and inductors using impedance**
  - $Z_R = R$ **in ohms**
  - $Z_L = sL$ **in ohms**
  - $Z_C = 1/sC$ **in ohms**
- **All circuit and network theorems still apply**



Series circuit – common current

$Z_T = Z_1 + Z_2 + Z_3$



Parallel circuit – common voltage

$Z_T = Z_1Z_2 /(Z_1+Z_2)$

Impedance concept extended to model time variation

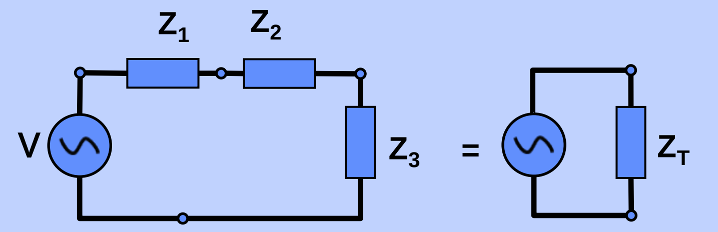
Circuit Theory - Complex Impedance

- **Given AC or sinusoidal excitations with complex exponential functions of time and frequency,**
  - **v** = V $e^{j\omega t}$
  - **i** = I $e^{j\omega t}$

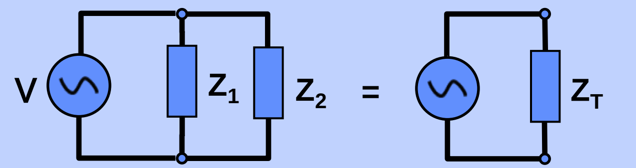
- **Impedance is the ratio of voltage to current***
  - **Z = v/i in ohms**

- **We can model resistors, capacitors and inductors using complex impedance**
  - Z_R = R **in ohms**
  - Z_L = $j\omega L$ **in ohms**
  - Z_C = $1/j\omega C$ **in ohms**

- **All circuit and network theorems still apply**



Series circuit – Common Current
$Z_T = Z_1 + Z_2 + Z_3$

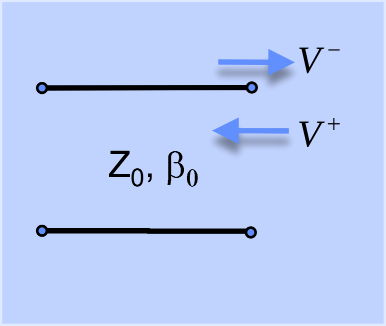


Parallel circuit – Common Voltage
$Z_T = Z_1Z_2 / (Z_1+Z_2)$

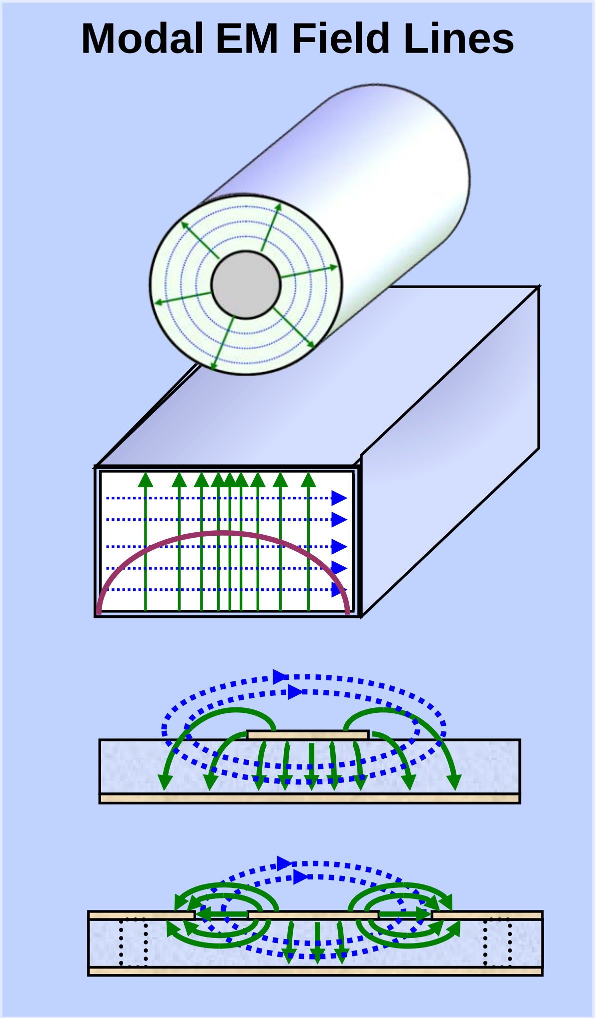
Complex impedance used to model sinusoidal time variance

Transmission Line Impedance

- **Voltage and current are guided through the circuit in waves that travel along the line**
  - $\mathbf{v}^{\pm}(z) = V e^{j\omega t} e^{\pm j\beta z}$
  - $\mathbf{i}^{\pm}(z) = I e^{j\omega t} e^{\pm j\beta z}$



- **A characteristic impedance can be defined for the traveling wave as the ratio of V and I**
  - $Z_0 = V/I$
- **Impedance is determined by the cross-sectional geometry of the line and the mode of propagation**
  - **Lines are operated such that only one mode propagates**
  - **Higher order modes are called "evanescent" modes**



Characteristic impedance used to model transmission lines

Transmission Line Circuit

- **In general the total voltage and current on the line is the sum of two traveling waves**

$$V_L = V^+ + V^- \qquad I_L = \frac{V^+ - V^-}{Z_0}$$

- **At the load the voltage-current ratio is**

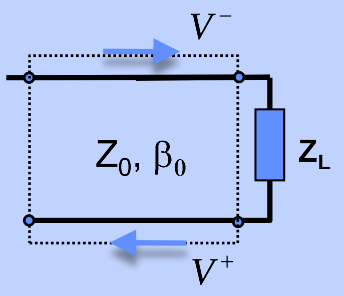
$$Z_L = \frac{V_L}{I_L} = \frac{V^+ + V^-}{V^+ - V^-} Z_0$$

- **Solve for the voltage wave in terms of impedance**

$$V^+ = \frac{Z_L - Z_0}{Z_L + Z_0} V^-$$

- **Voltage reflection coefficient and voltage standing wave ratio**

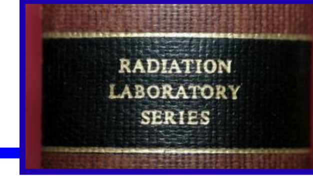
$$\boxed{\frac{V^-}{V^+} = \Gamma = \frac{Z_L - Z_o}{Z_L + Z_o}} \qquad \boxed{VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}}$$

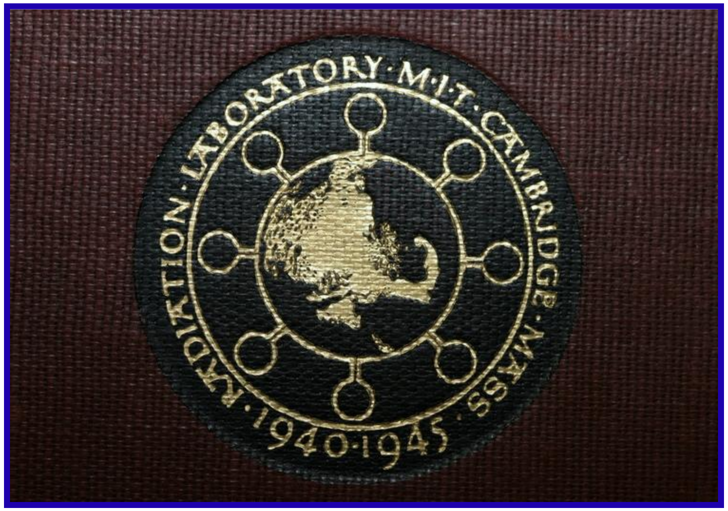


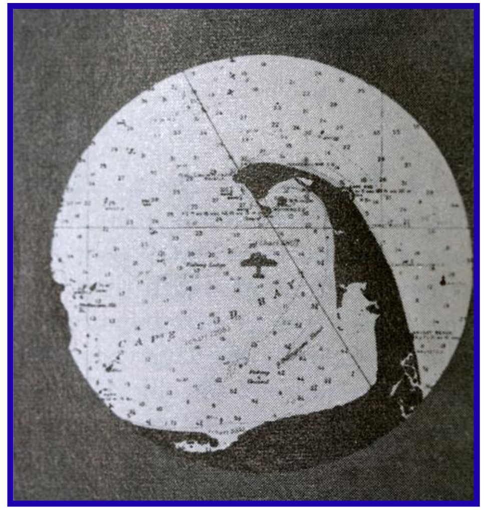
Loaded Transmission Line

No reflections and no standing waves if the load impedance matches the line

Microwave Networks - History



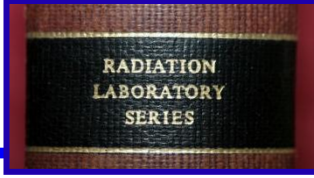




- **The MIT Radiation Laboratory developed RADAR technology for the war effort from 1940-1945**
- **MIT Rad. Lab. 28 Volume Series**

> **"Authors were selected to remain at work at MIT for six months or more after the work of the Radiation Laboratory was complete. These volumes stand as a monument to this group…. and a memorial to the unnamed thousands of other scientists, engineers, and others …." – L.A. DuBridge, Lab Director**

“Principles of Microwave Circuits”



- Vol. 8 of the Rad Lab Series, 1948
- Authors were not yet full professors
  - C.G. Montgomery, Yale Physics
  - R.H. Dicke, Princeton Physics (Radiometer, Magic T)
  - E.M. Purcell, Harvard Physics (Nobel Prize ’52 NMR)

> “This volume is devoted to an exposition of the <u>impedance concept</u> and to the equivalent circuits of microwave devices.” – The Authors

- This book set the standard for future Microwave Engineering textbooks

Rad Lab Vol 8	Pozar 3rd edition TOC
– 0. Introduction	
– 1. EM waves	1. EM Theory
– 2. Waveguide as transmission lines	2. Transmission line theory
	3. Transmission lines and waveguides
– 3. Network theory	4. Microwave network analysis
– 4. Microwave circuit theorems	
– 5. Waveguide circuit elements	5. Impedance matching and tuning
– 6. Resonant cavities	6. Microwave Resonators
– 7. Radial transmission lines	
– 8. Junctions with several arms	7. Power dividers and couplers

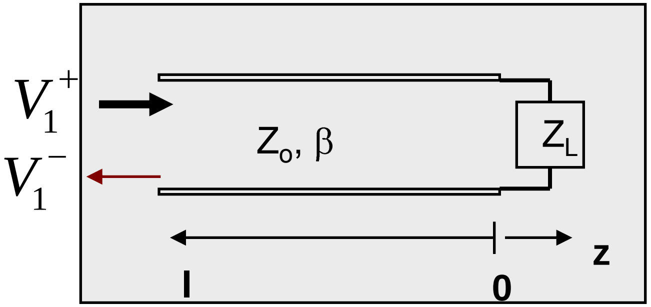
Three step process: EM → Transmission Lines → Networks

RF Component - One Port Behavior

- **Behavior of a one port**
  - **Specified by one scattering parameter the reflection coefficient**

$$\frac{V^-}{V^+} = \Gamma = \frac{Z_L - Z_o}{Z_L + Z_o}$$

- **Experimental solution**
  - **Directly connect a source as the free parameter (incident voltage wave)**
  - **Measure the dependent parameter ("reflected" wave)**
  - **Compute the reflection coefficient**

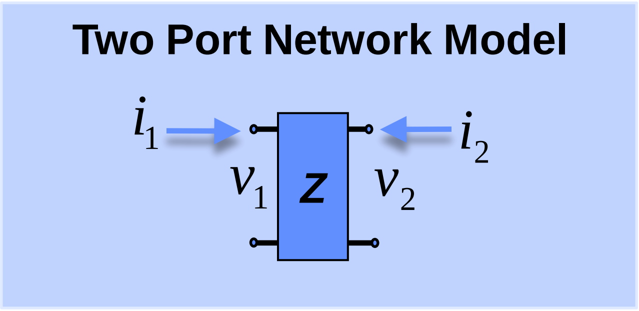


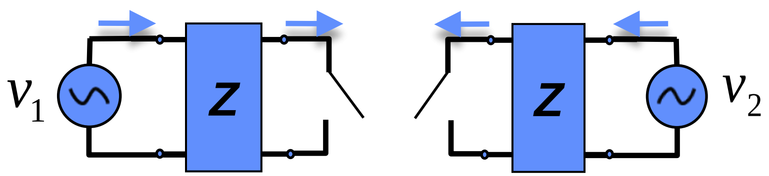
- **Analytic general solution**
  - **Given full 3D geometry of the component**
  - **Solve for electromagnetic (EM) fields**
  - **Determine reflection coefficient**

For a single port network the only scattering term is a reflection

Circuit Component Two Port Behavior

- Behavior of a two port
  - Specified by four parameters
  - Only two are dependent parameters
- Experimental general solution
  - Remove one of the free parameters (open circuit or short circuit condition)
  - Directly connect a voltage or current source as the free parameter
  - Measure the two dependent parameters
  - Repeat to determine current-voltage relationship at both <u>ports</u>
- Analytic general solution
  - Given full 3D geometry of the component
  - Solve for electromagnetic (EM) fields
  - Determine current-voltage relationship at the <u>ports</u>





$$z_{11} = \frac{v_1}{i_1}\bigg|_{i_2=0} \qquad z_{21} = \frac{v_2}{i_1}\bigg|_{i_2=0}$$

$$z_{22} = \frac{v_2}{i_2}\bigg|_{i_1=0} \qquad z_{12} = \frac{v_1}{i_2}\bigg|_{i_1=0}$$

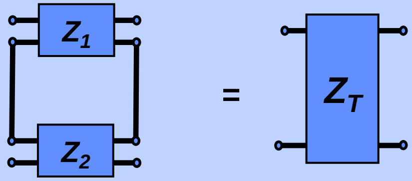
$$Z = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix}$$

Circuit Theory – Two Port Impedance

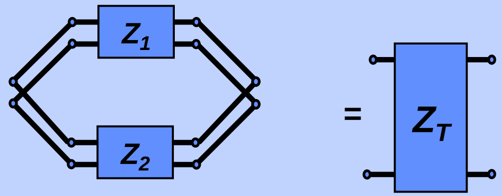
- **Two port impedance given in terms of a matrix**

$$Z = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}$$

- **All network theorems still apply**



Series circuit
$Z_T = Z_1 + Z_2$



Parallel circuit
$Z_T = Z_1 Z_2 /(Z_1+Z_2)$

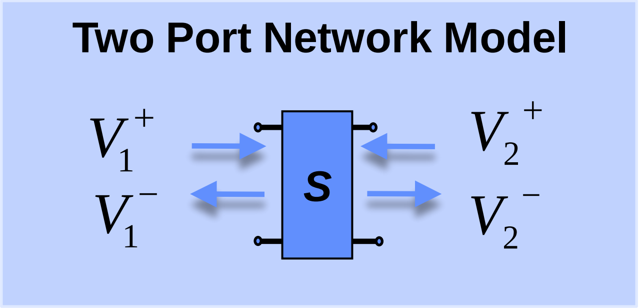
Two port network components are connected to form networks

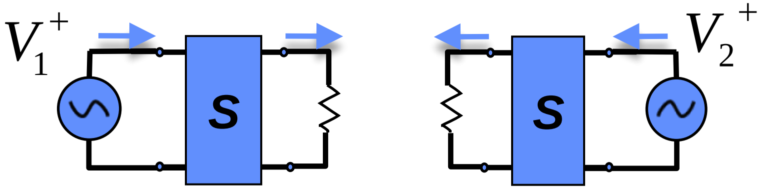
RF Component Two Port Behavior

- **Behavior of a two port**
  - **Specified by four <u>scattering</u> parameters**
  - **Only two are dependent parameters**

- **Experimental general solution**
  - **Remove one of the free parameters (Perfectly terminated ports)**
  - **Directly connect a source as the free parameter (incident voltage wave)**
  - **Measure the two dependent parameters (scattered “outgoing” waves)**
  - **Repeat to determine voltage wave relationship at both ports**

- **Analytic general solution**
  - **Given full 3D geometry of the component**
  - **Solve for electromagnetic (EM) fields**
  - **Determine scattering parameters at the ports**





$$S_{11} = \left.\frac{V_1^-}{V_1^+}\right|_{V_2^+=0} \qquad S_{21} = \left.\frac{V_2^-}{V_1^+}\right|_{V_2^+=0}$$

$$S_{22} = \left.\frac{V_2^-}{V_2^+}\right|_{V_1^+=0} \qquad S_{12} = \left.\frac{V_1^-}{V_2^+}\right|_{V_1^+=0}$$

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}$$

Symmetric Lossless Two Port

- **Four terms reduce to one**
  - **Reflected power is Γ^2**
  - **Transmitted power is 1- Γ^2**

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}$$

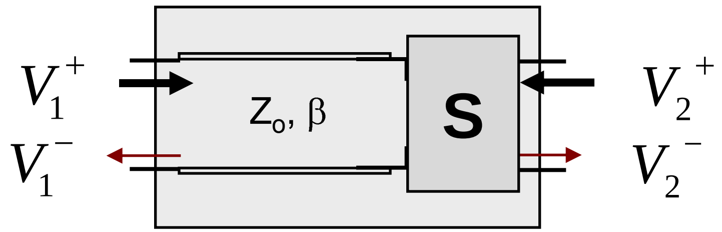
symmetric lossless 2-port

$$|S_{11}|^2 = |S_{22}|^2 = \Gamma^2$$

$$S_{12} = S_{21}$$

$$|S_{21}|^2 = 1 - \Gamma^2$$

Cascaded Transmission Lines



For 2-port shown on left

$$S'_{11} = S_{11} e^{-j\beta 2l}$$ **Twice the phase**

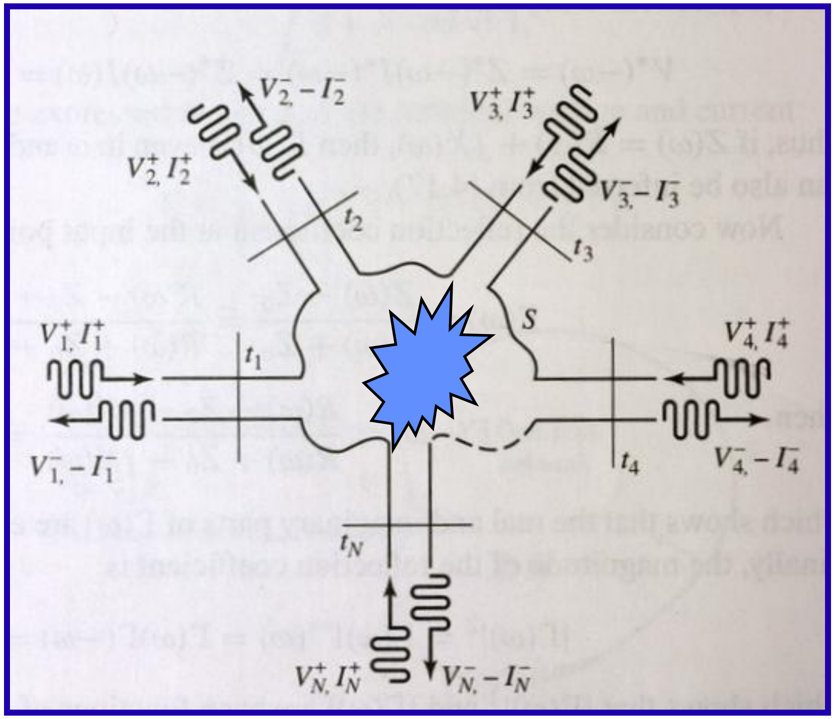
$$S'_{12} = S_{12} e^{-j\beta l}$$

$$S'_{22} = S_{22}$$

$$S'_{21} = S_{21} e^{-j\beta l}$$

Adding a longer transmission line simply adds a phase shift

N-port Scattering Matrix



$$\begin{bmatrix} V_1^- \\ V_2^- \\ \vdots \\ V_N^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1N} \\ S_{21} & & & \vdots \\ \vdots & & & \\ S_{N1} & \cdots & & S_{NN} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \\ \vdots \\ V_N^+ \end{bmatrix},$$

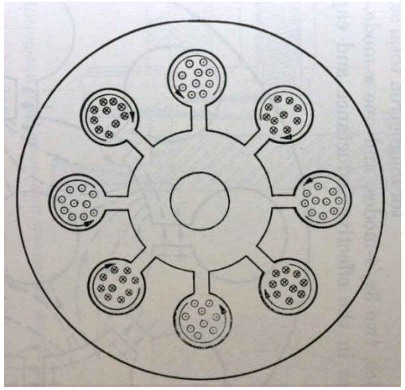
$$[V^-] = [S][V^+].$$

$$S_{ij} = \left.\frac{V_i^-}{V_j^+}\right|_{V_k^+=0 \;\; for \;\; k \neq j}$$

- **N^2 parameters provide a complete description of an N-port**
- **Use network theory to make life easier**
  - **Passive lossless networks are symmetric and unitary**
  - **Symmetry reduces the number of measurements to N(N+1)/2**

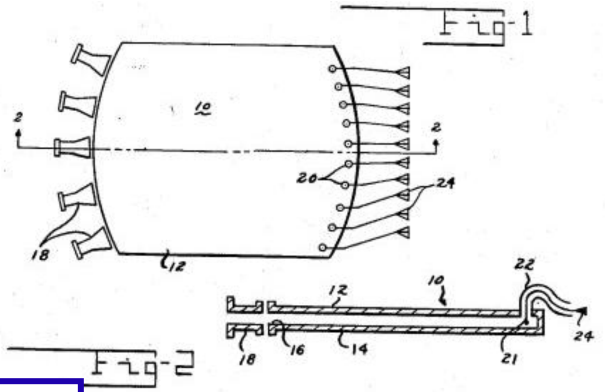
The thing in the black box is completely determined by what it scatters

Network Topologies



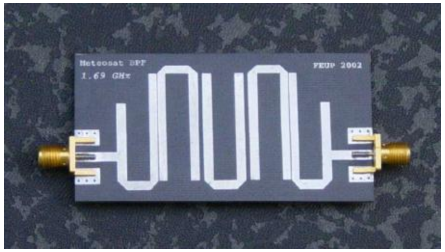
Multi Cavity Resonator*

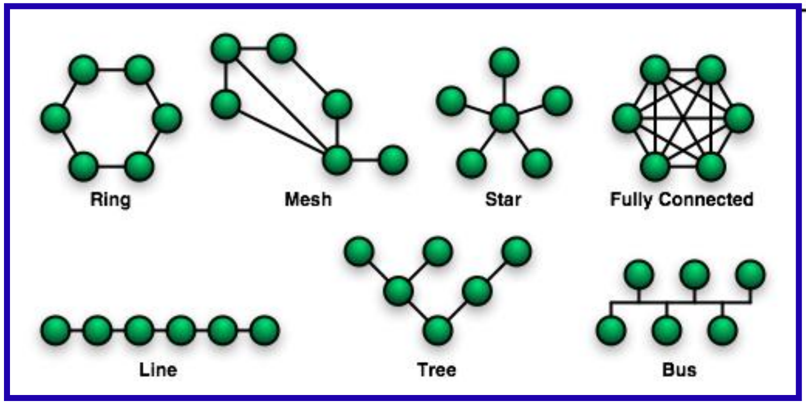
Magic T

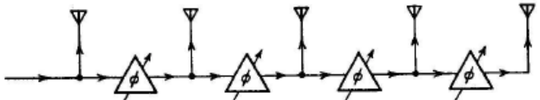


Rotman Lens

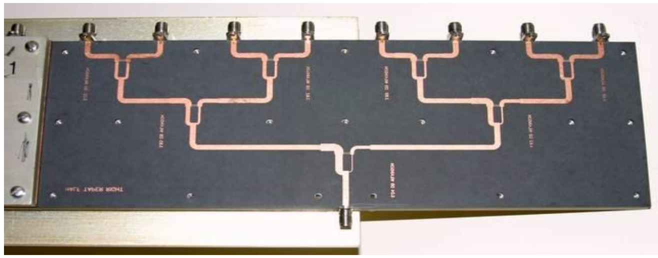
4 Section Filter







Series Feed Network



Network Theory

- **Network analysis**
  - **Determine the response of a network to a given excitation**
    - **Today this is done in simulation augmented with measurements**
- **Network synthesis**
  - **Determine the network that will produce a desired response given an excitation**
    - **Desired performance can be described in many ways**
  - **Solution doesn't necessarily exist**
    - **Necessary conditions**
    - **Sufficient conditions**
    - **Need to work under those conditions**
  - **Solution is not unique**
    - **Infinite number of possible "Equivalent" solutions exist**
    - **Look to realization constraints (cost, complexity, sensitivity…)**
- **Network realization**

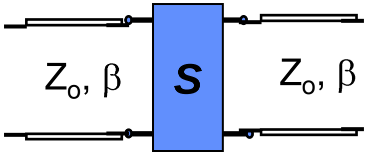
These topics are covered extensively in other lectures: impedance matching, filter design, amplifier design…

Outline

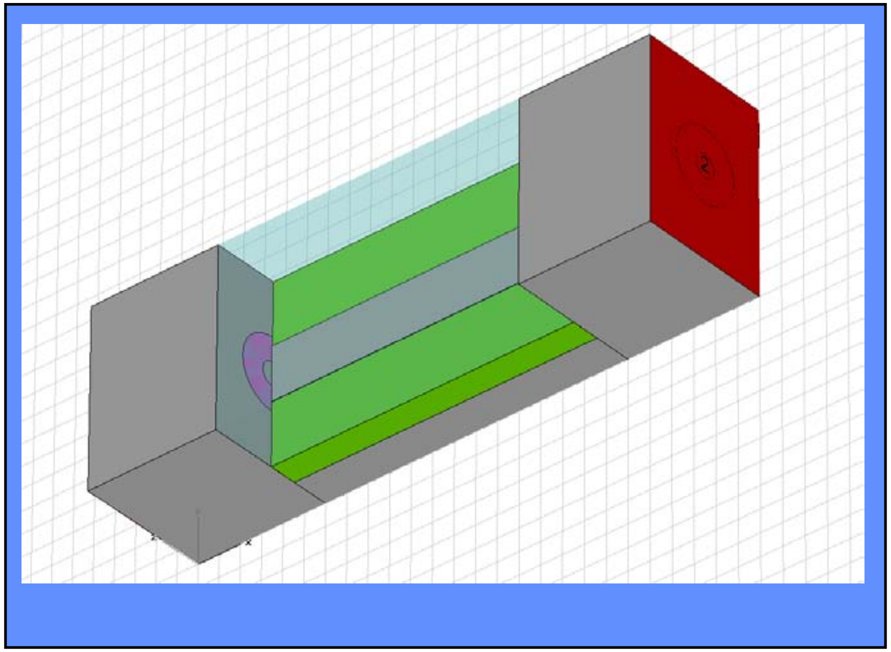
- Introduction
- Circuit and Network Theory
- RF Measurements
- RF Design/Build
- Summary

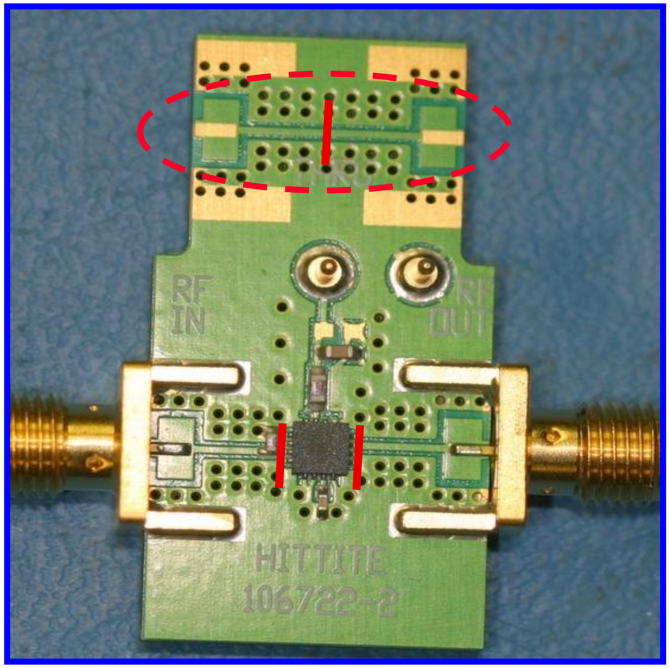
Measuring an RF component

Specific S parameters are summarized in spec sheets, with full parameters given as electronic files, or you can measure them

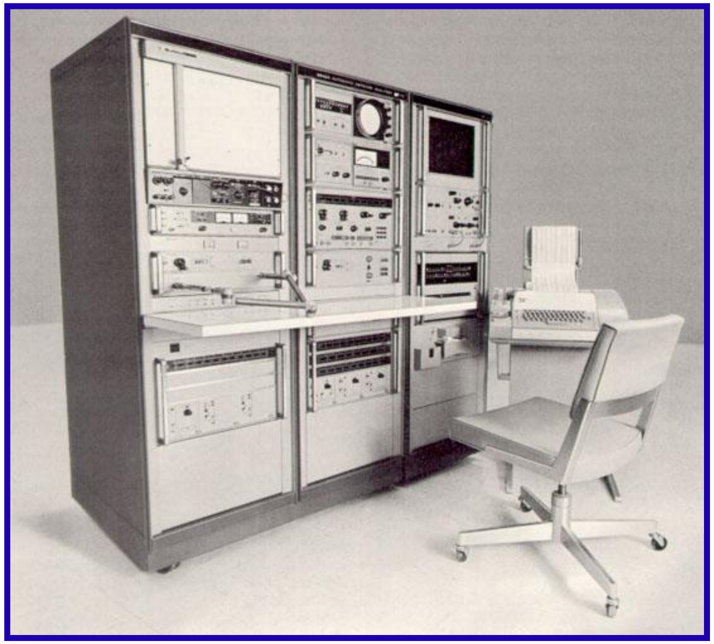


CAD model of evaluation board

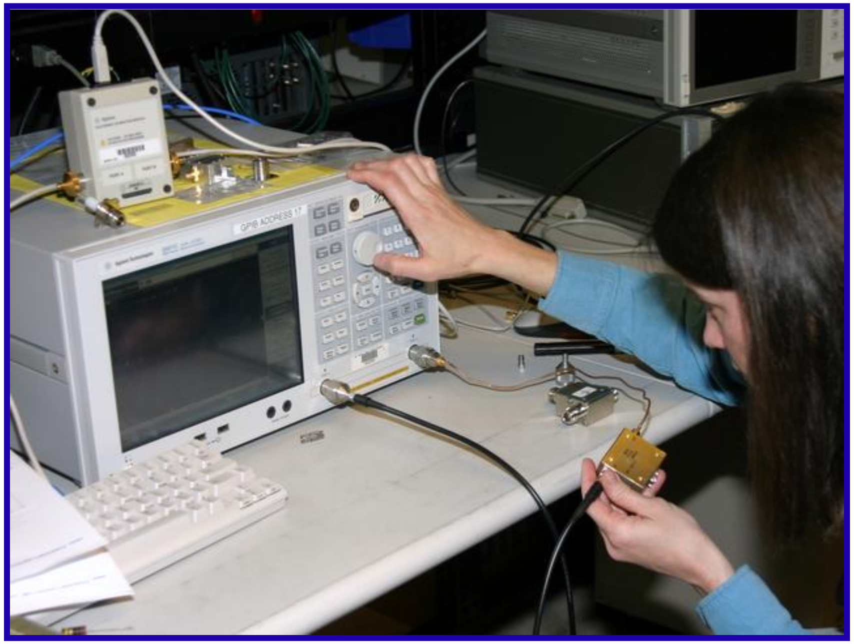




Vector Network Analyzer



HP 8542A Automatic Network Analyzer *



Modern network analyzer measurement**

- Corresponds to frequency domain network analysis
- Narrow band signal is swept into the DUT through a calibrated reference plane
- Direct measurement of 2-port S-parameters (Measures S_{11}, S_{12}, S_{21}, and S_{22})
- Multiport networks are measured two ports at a time terminating all other ports

* Source: Hewlett Packard Journal, February 1970, page 3.

** Kristan Tuttle Gr 39

Network Analyzer Calibration

$$S_{ij} = \left. \frac{V_i^-}{V_j^+} \right|_{V_k^+ = 0 \ \ for\ \ k \neq j}$$

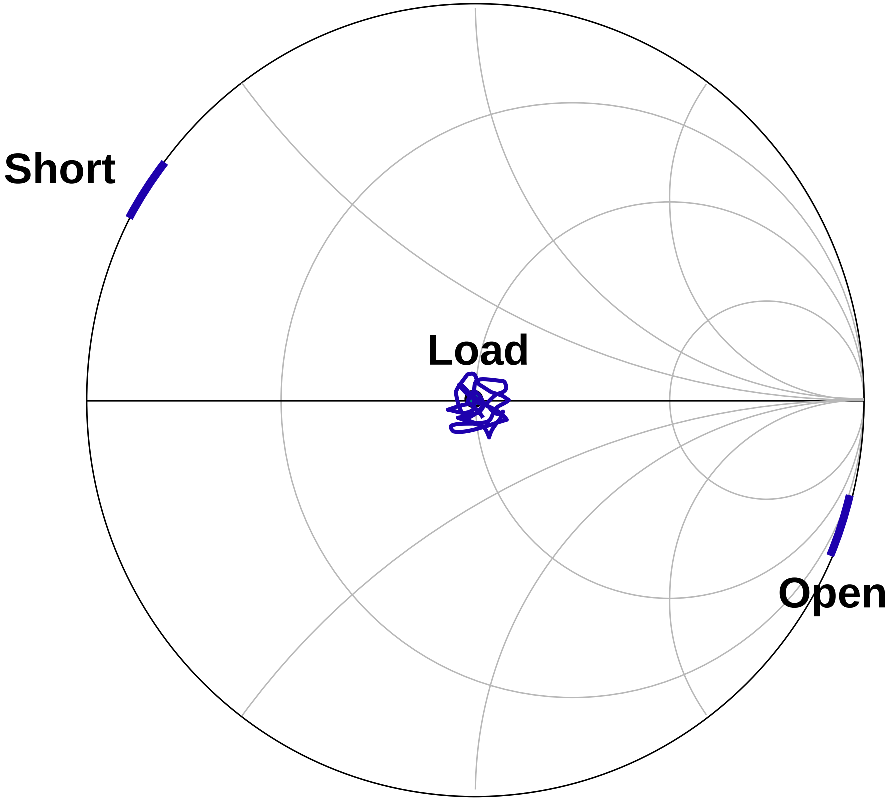
- **Purpose of calibration:**
  - **Definition of S-parameters require matched ports**
  - **Remove systematic errors caused by the equipment**
  - **Enhance accuracy, repeatability, stability**

- **When should you re-calibrate?**
  - **You change settings on the analyzer (frequency band, sweep time…)**
  - **You change the test set-up (move cables, change sex on connectors…)**
  - **Someone else uses the analyzer**

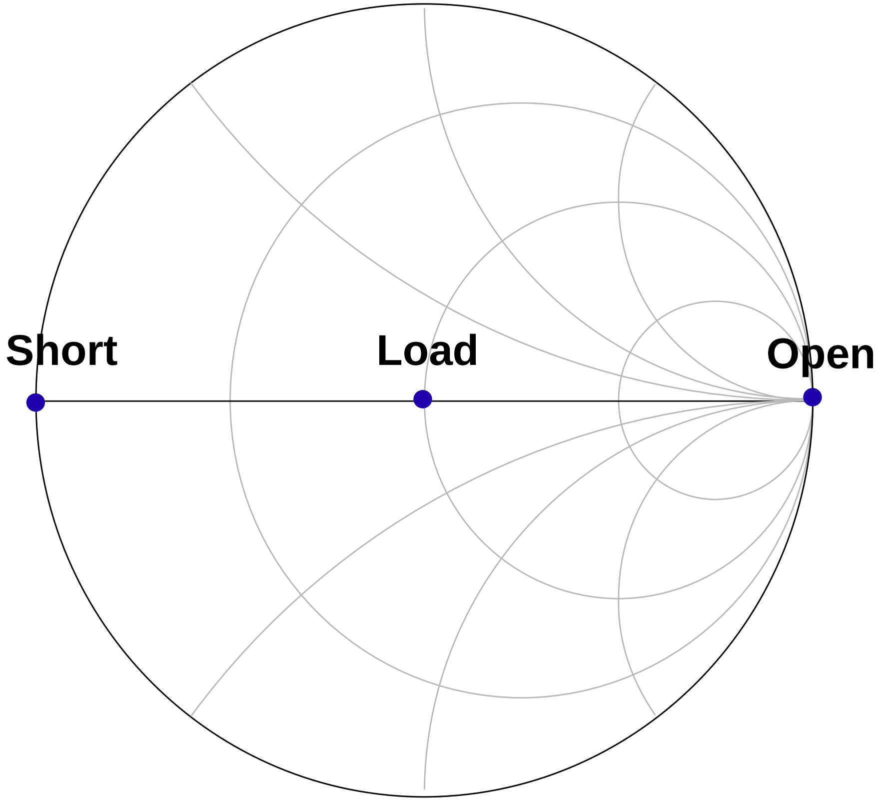
- **Types of calibration**
  - **Electronic calibration is the standard used today**
  - **Manual calibration takes longer**
    - **Single port cal. using calibration kit (2-5 min.)**
    - **Full two port cal. (5 - 10 min. sliding load optional)**

Single Port Calibration Results

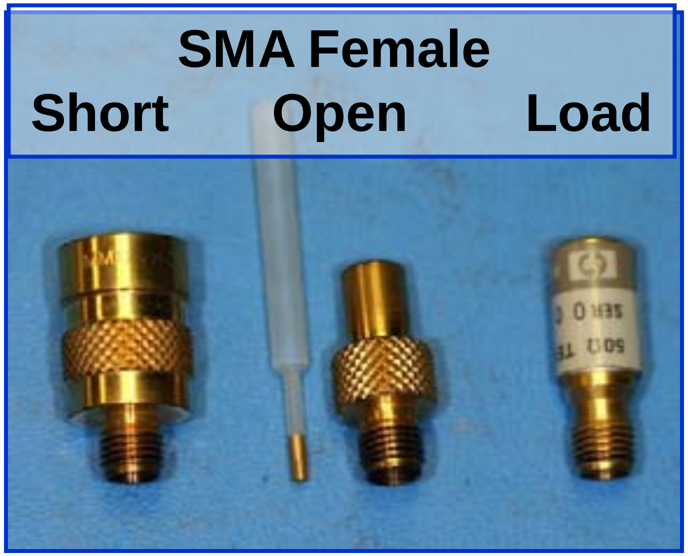
Stale or no calibration

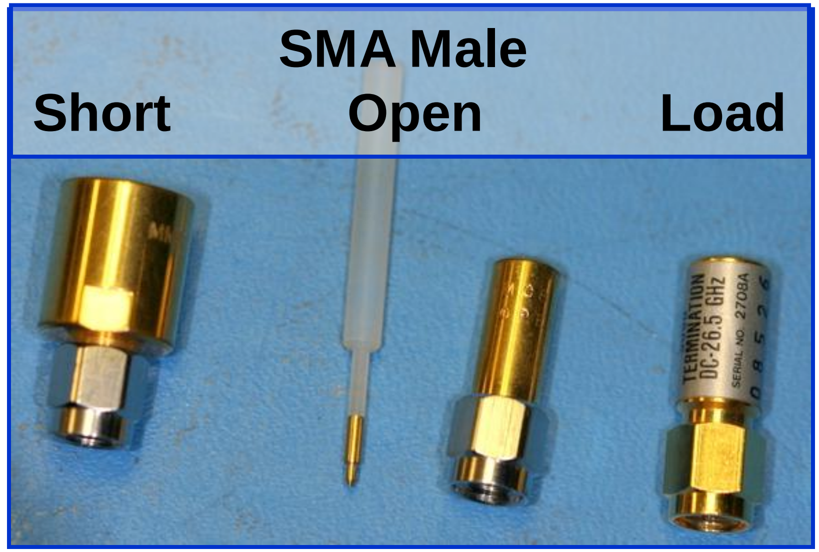


Fresh calibration



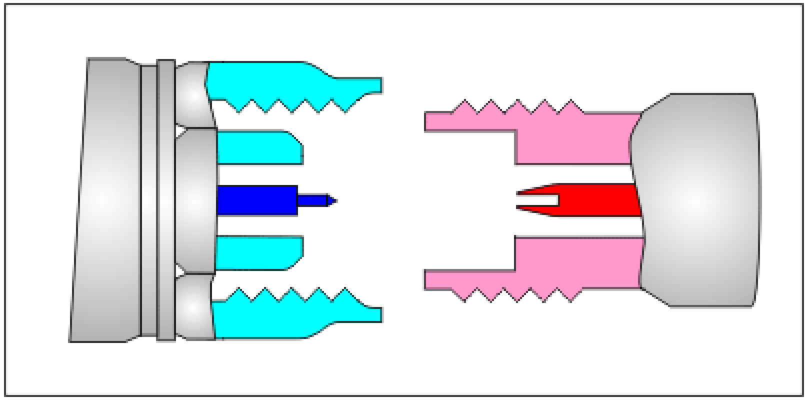
Coaxial SOL Calibration Standards





- **Make sure connectors are clean and properly gauged**
- **Use a torque wrench**
- **Turn the coupling nut, not the standard**

Coaxial Mating Connectors



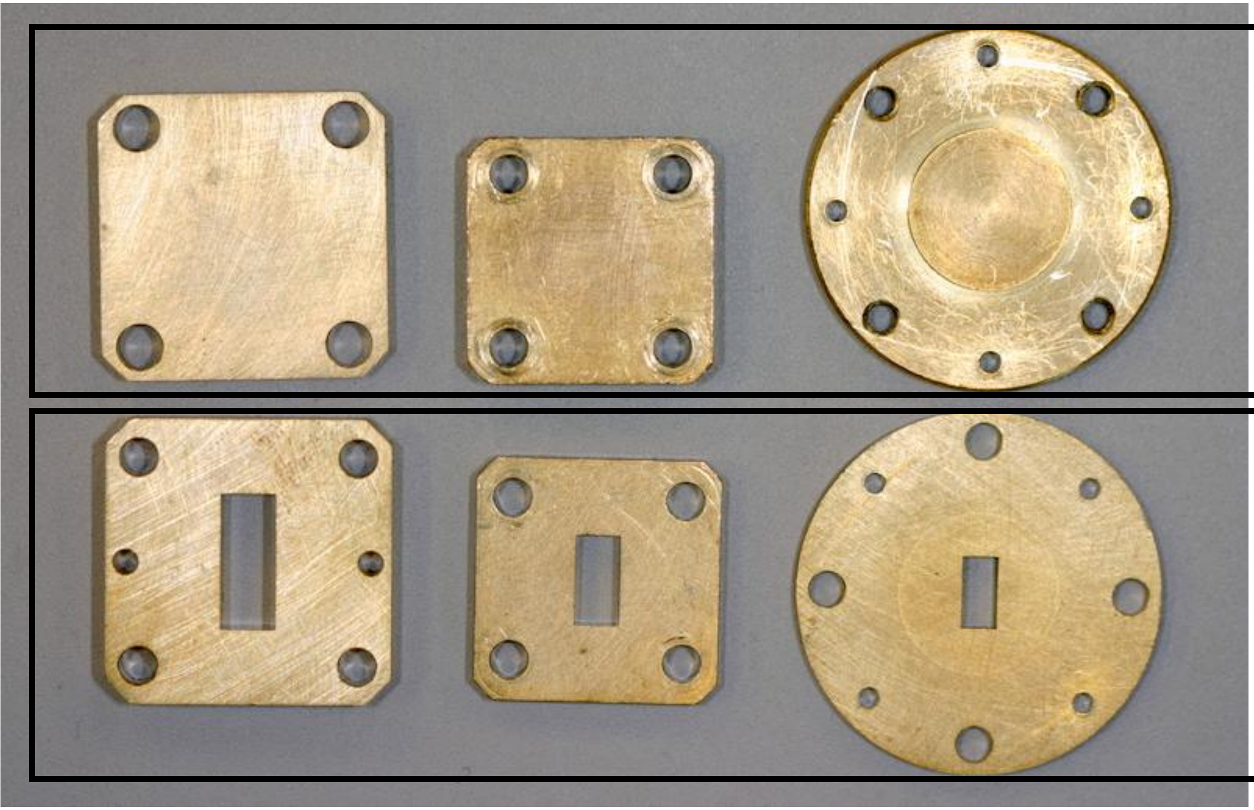
*

Courtesy of Agilent Technologies. Used with permission.

- **Threaded connectors operate over much wider vibration environments**
  - **Twist or push on are easy to twist or push off**
- **Mating surfaces join to provide the reference plane**
  - **Joint is critical for repeatable measurements**
- **Female center pin has heat-treated beryllium copper fingers**
  - **Fingers are spring loaded to maintain physical pressure contact**
  - **Pressure may be too much an pull the center pin out**
  - **Broken fingers can easily short out connections**

*Thanks to Agilent's "connector care" web site

Waveguide TRL Calibration Standards

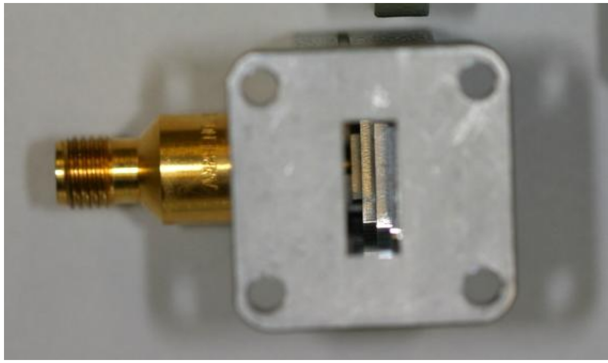


Reflect

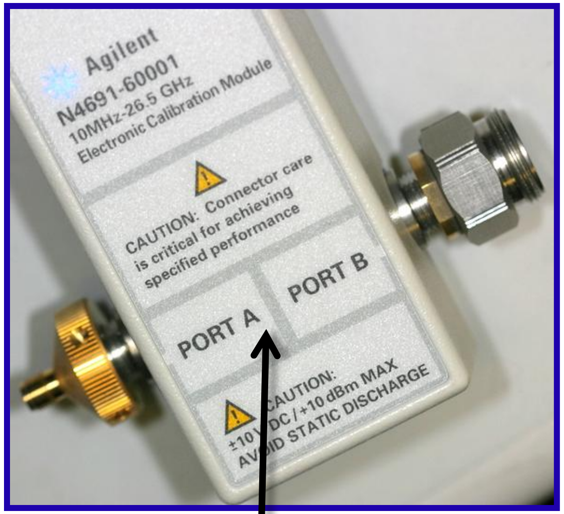
Line
(short section of waveguide)

Ku 15-20 GHz | **Ka 30 GHz** | **Q 40-50 GHz**

Thru measurement is a mating of the two waveguide reference planes



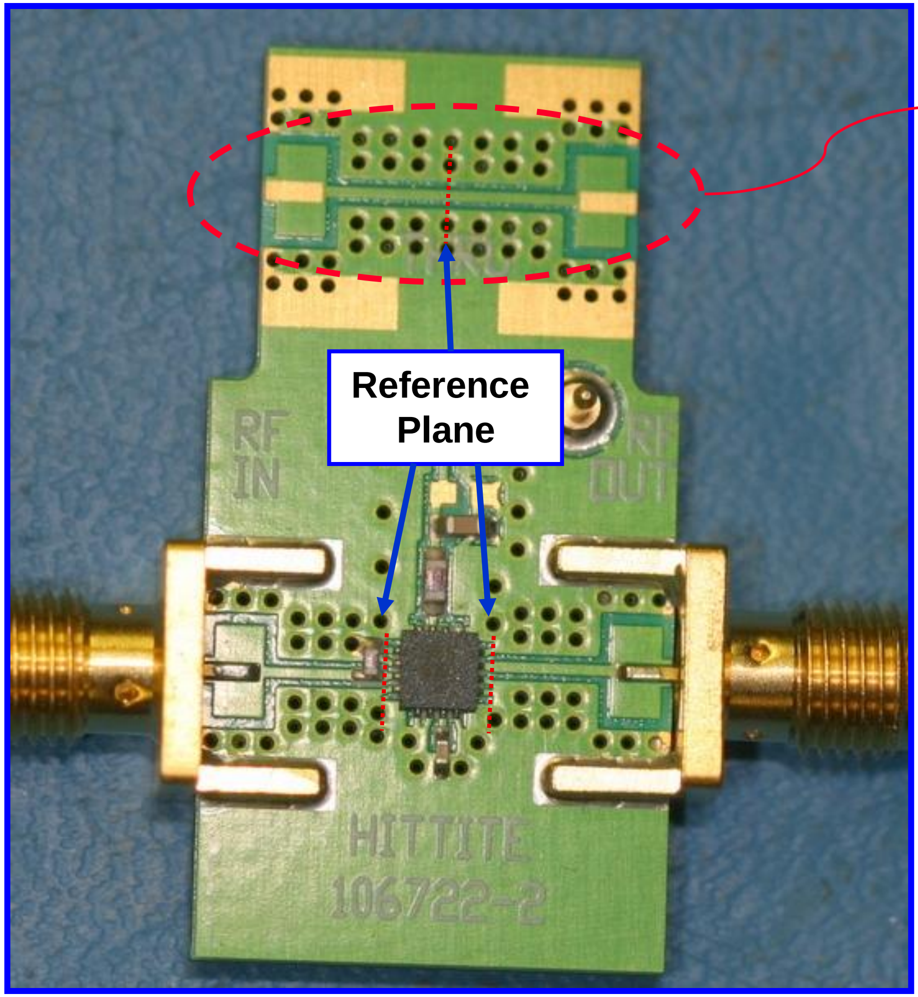
E-Cal Module



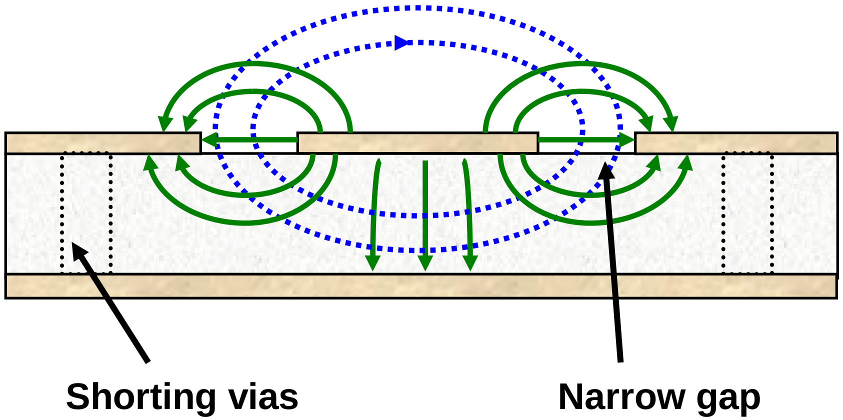
SOL Standards Built in

- Automated two-port calibration performed in 30 sec. using switching network
- Removes human error and tedium
- Temperature stability is maintained by in internal heat plate
- Connector care is still important!

Microwave Vendor Evaluation Board



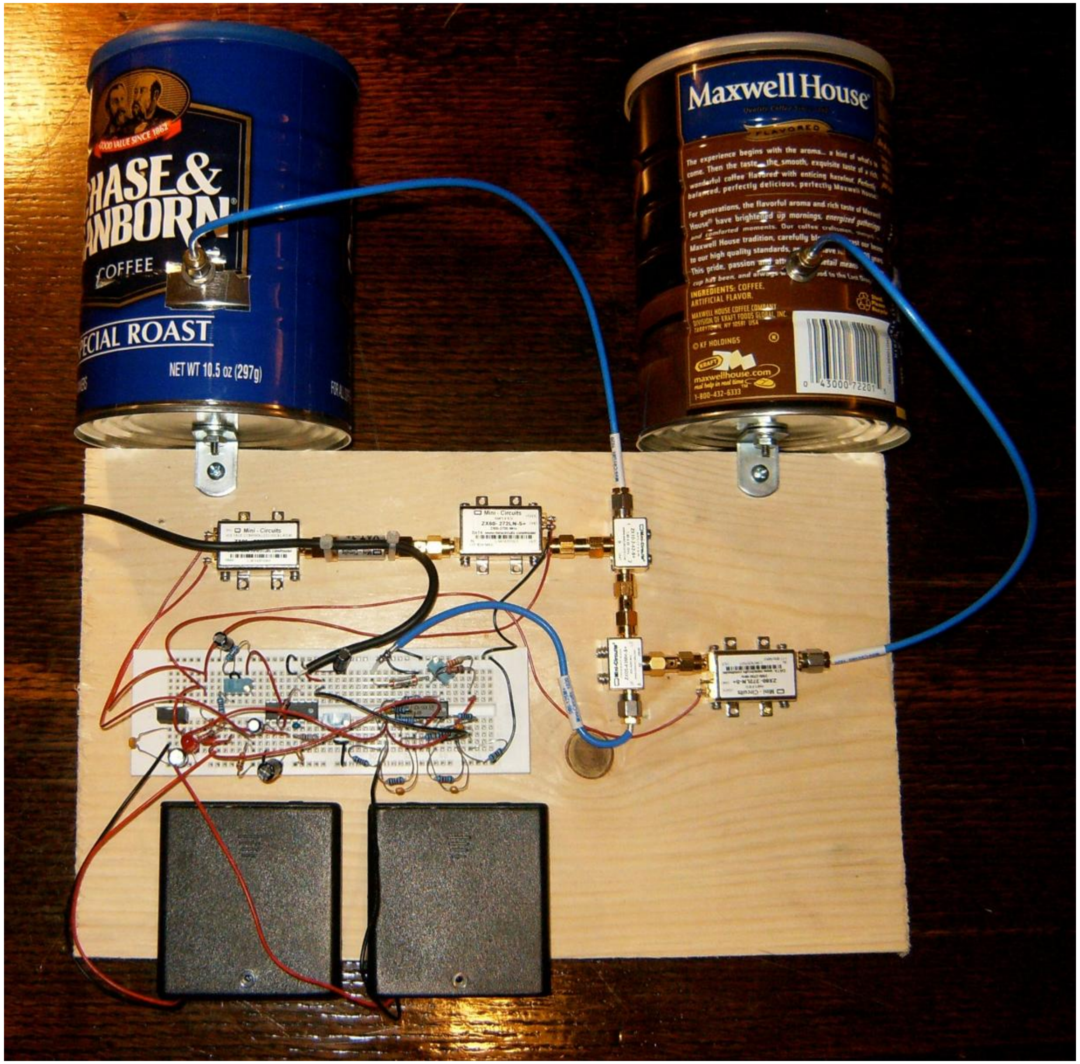
- Grounded coplanar waveguide
- Thru line is provided for calibration
- Remove the effects of waveguide transitions and transmission lines
- S-parameters are exported directly into simulations

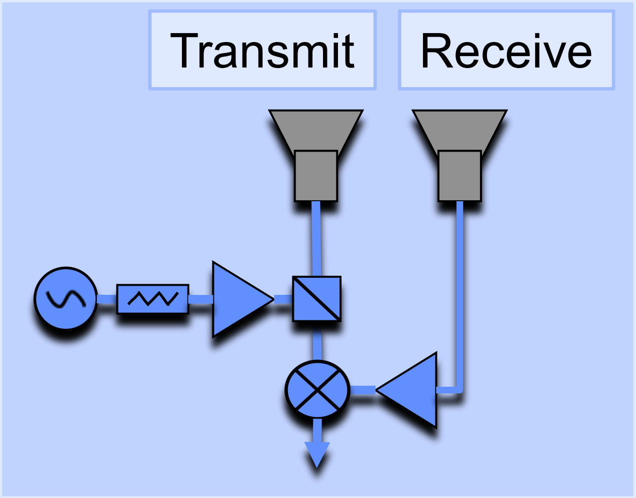


Outline

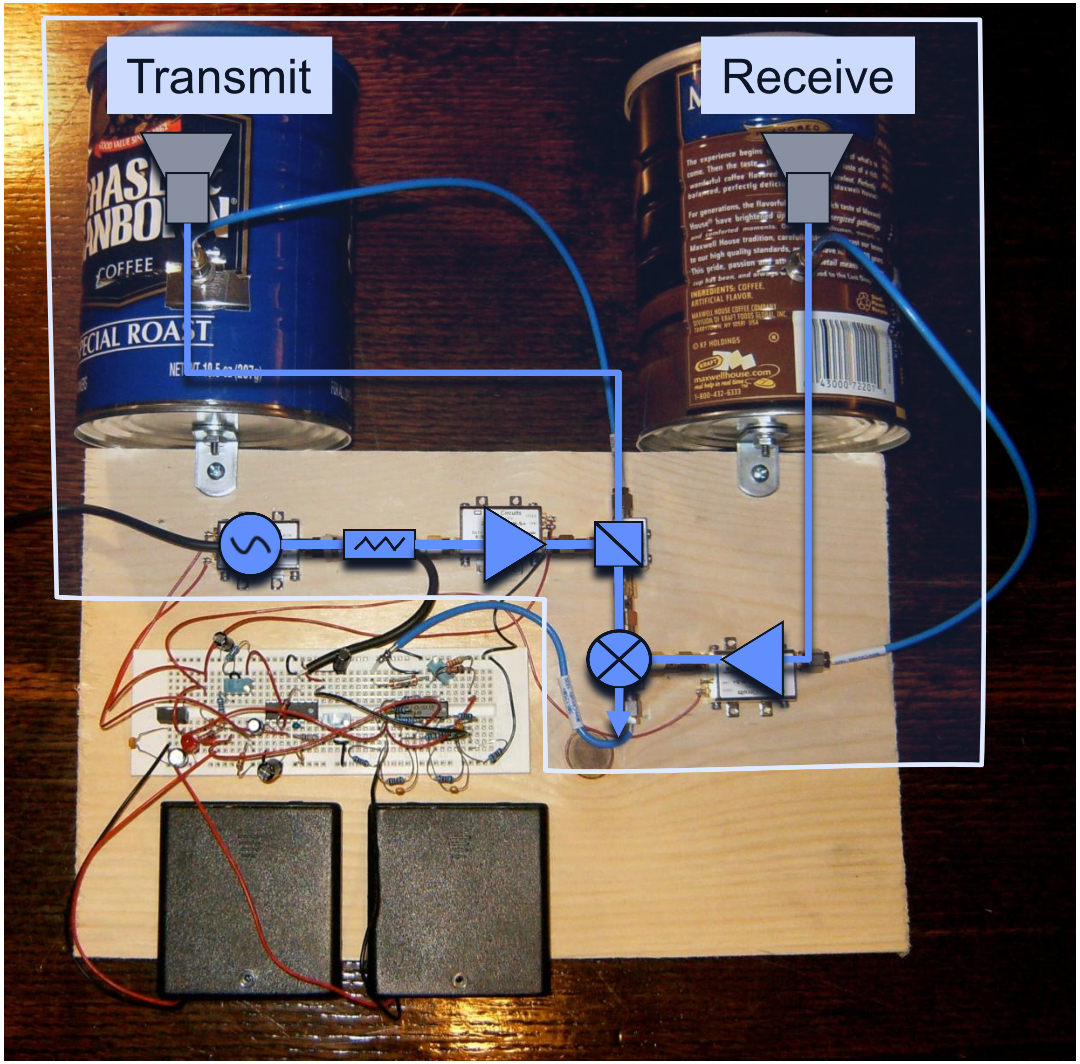
- Introduction
- Circuit and Network Theory
- RF Measurements
- **RF Design/Build**
- Summary

Radar RF Components

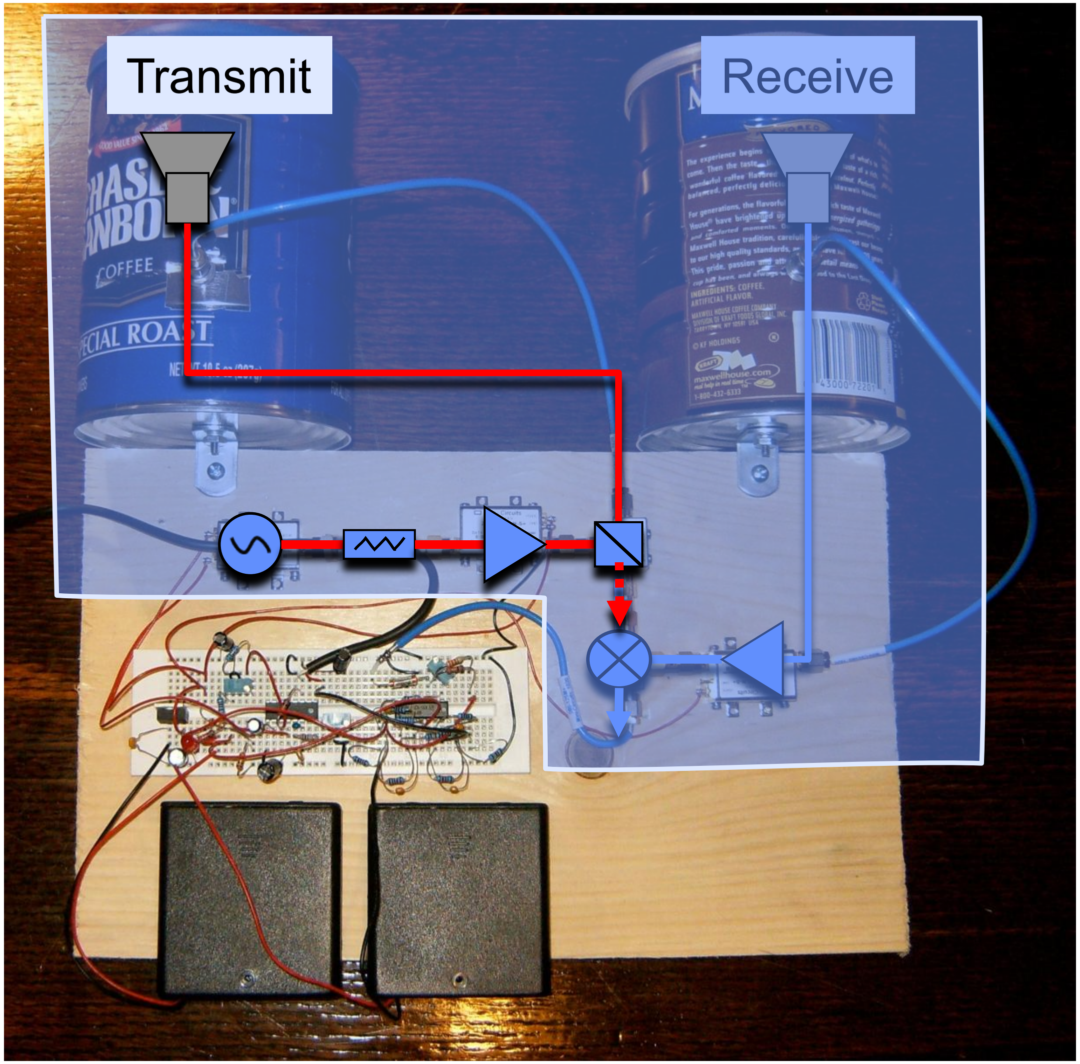




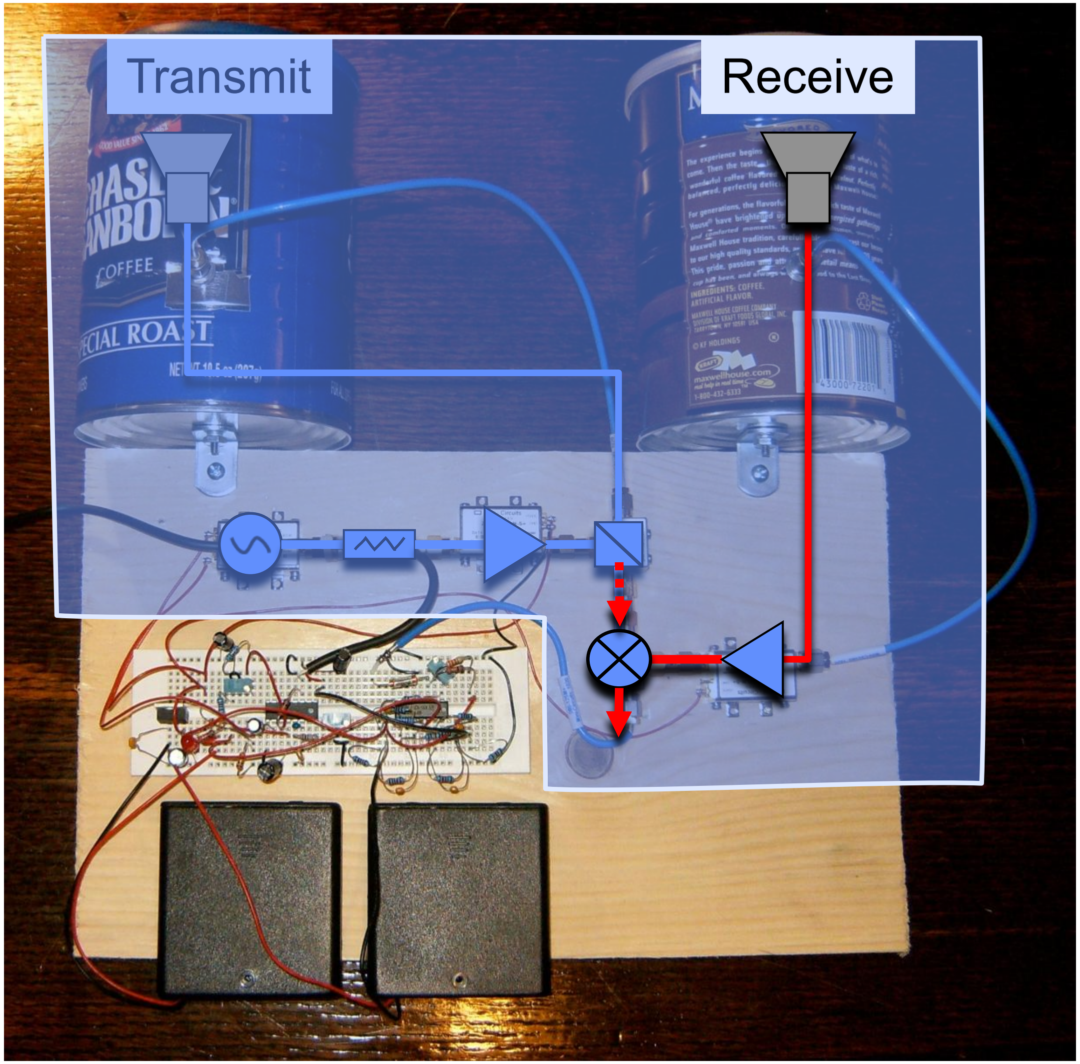
Radar RF Components



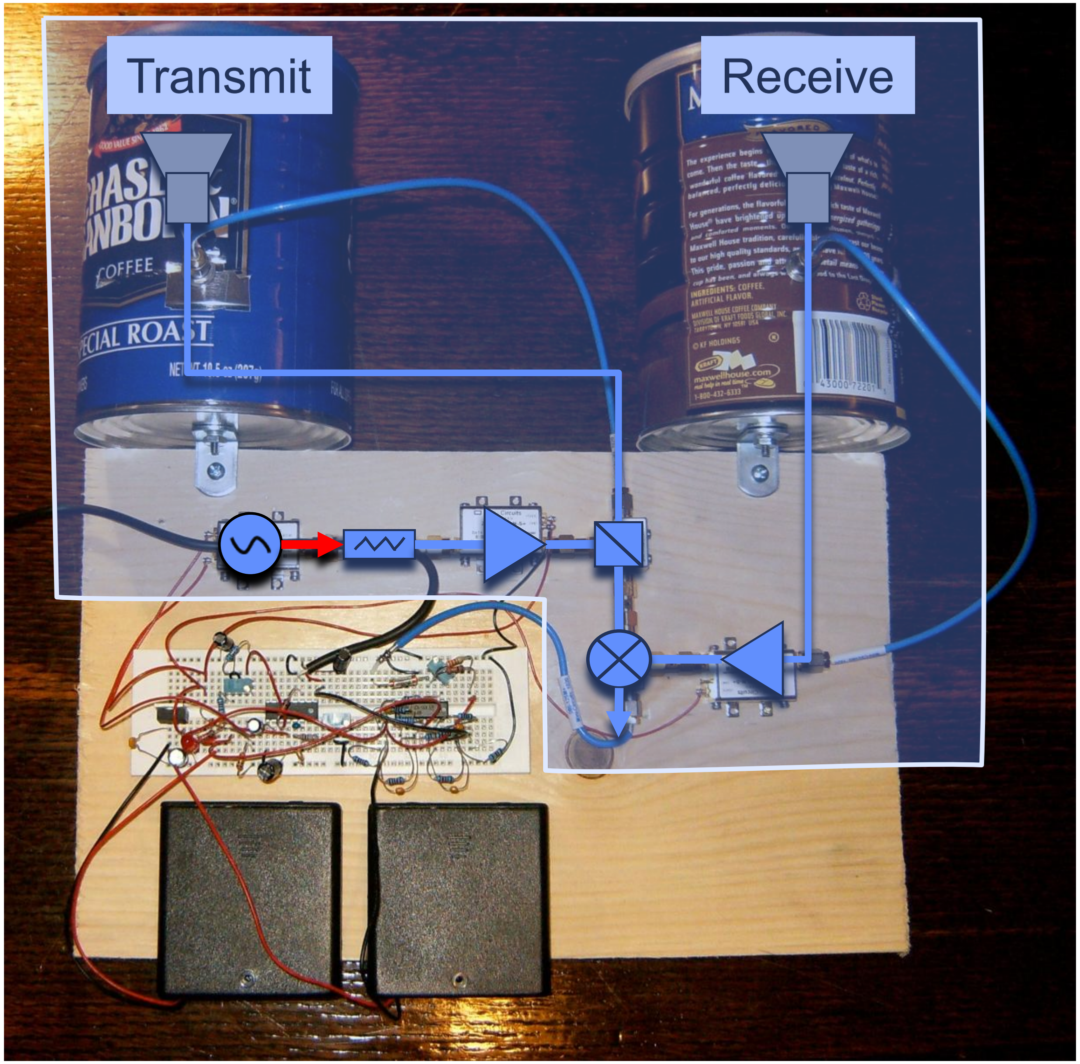
Transmit Chain

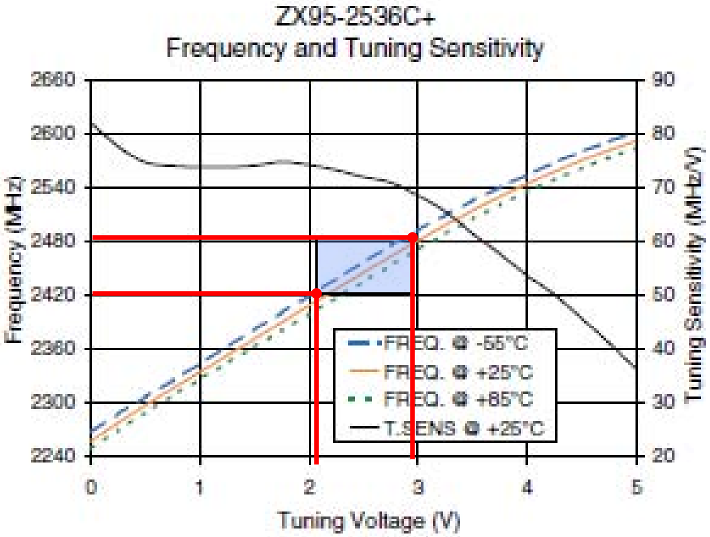


Receive Chain



Voltage Controlled Oscillator

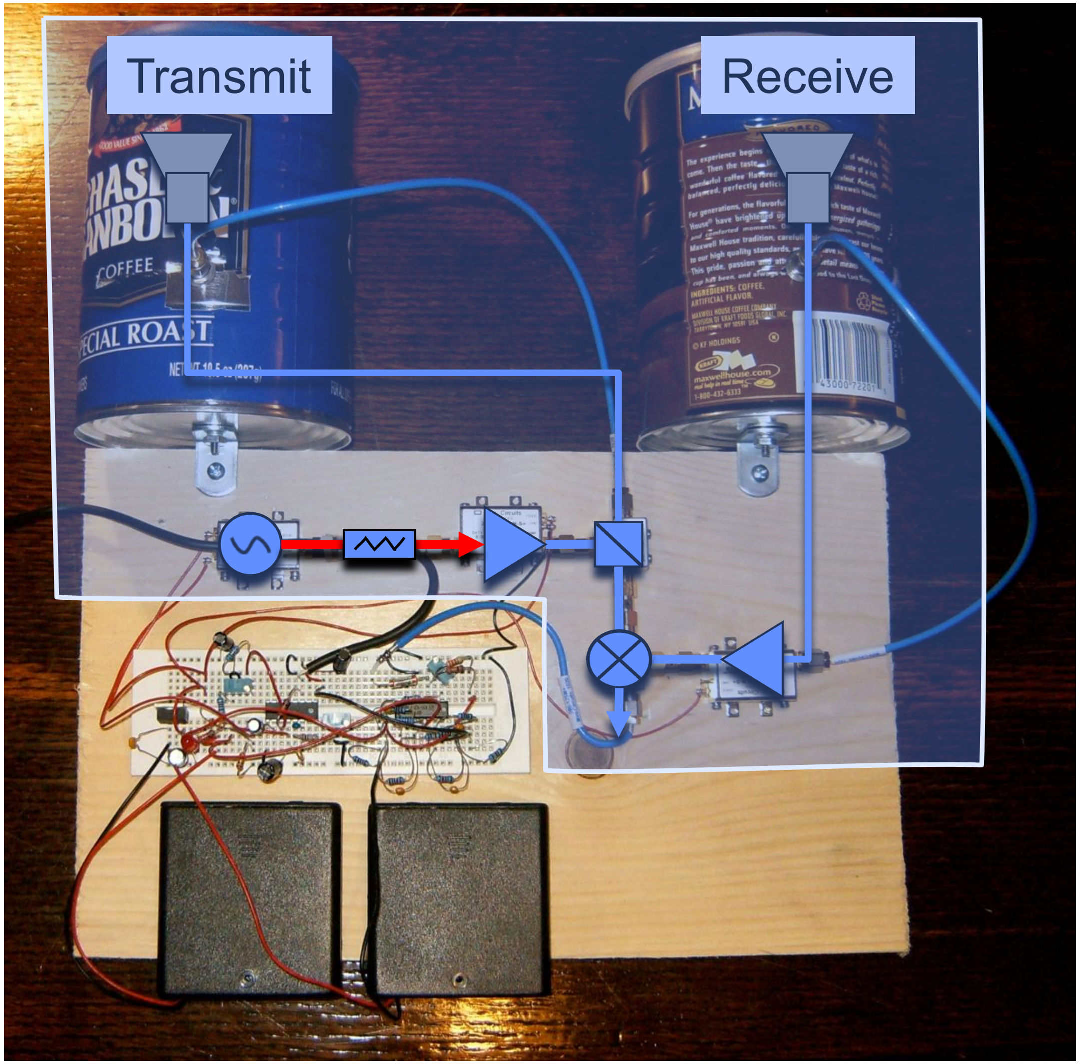


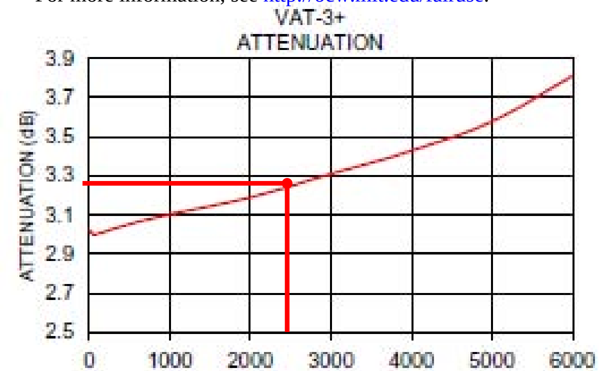


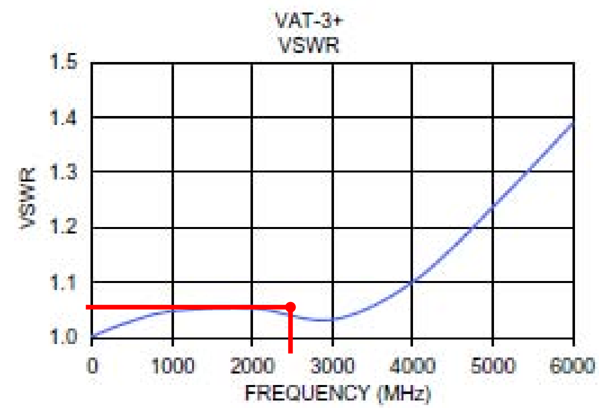
DC Power = .25 Watt

RF Power = 6 dBm

Attenuator



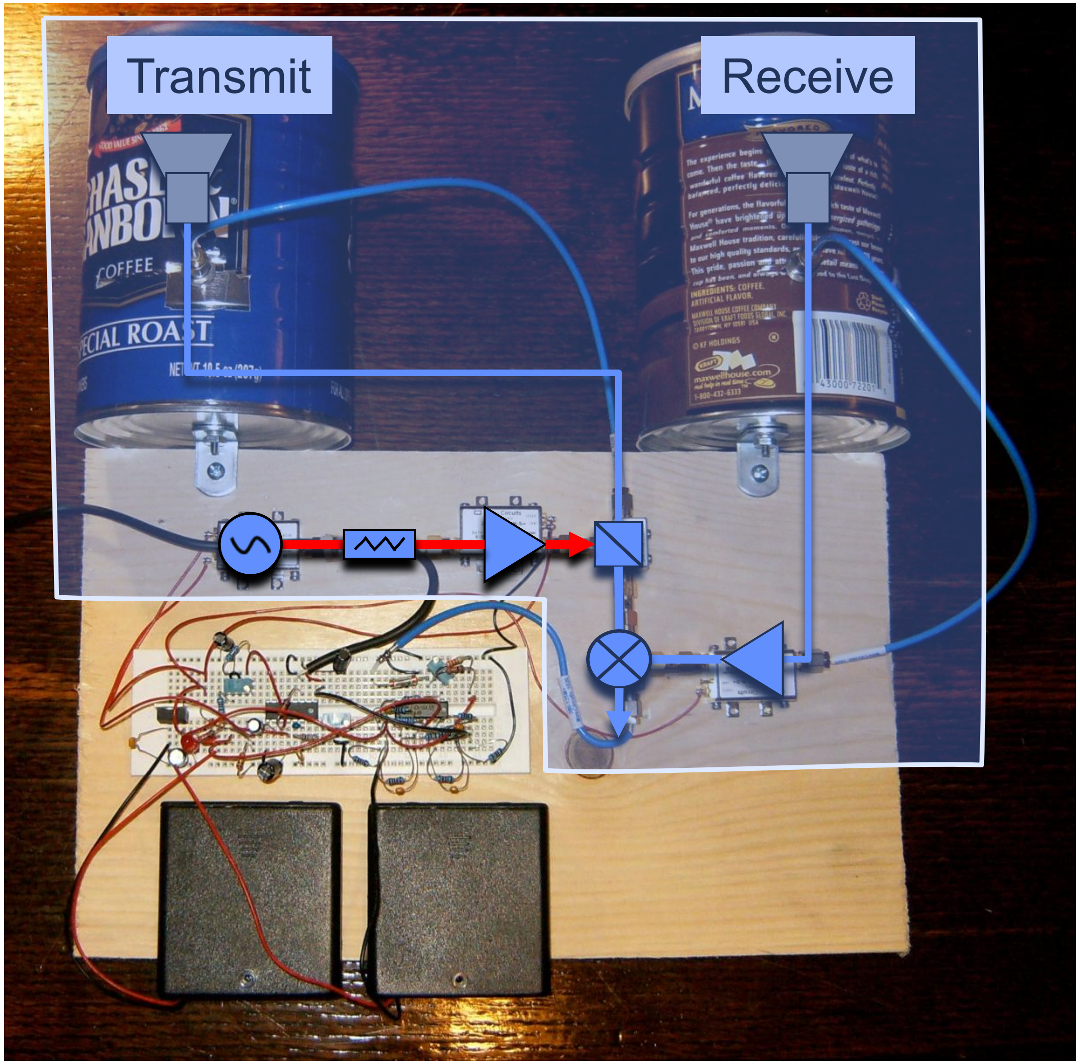


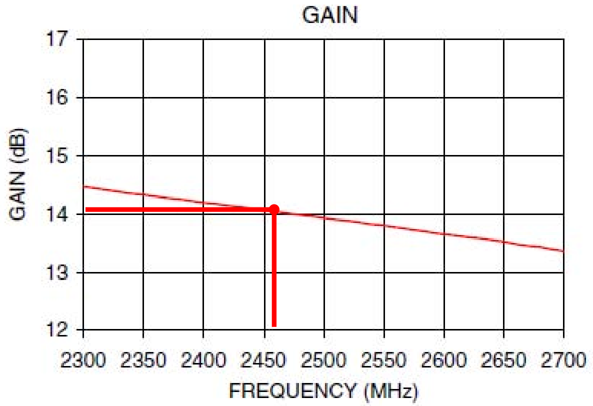


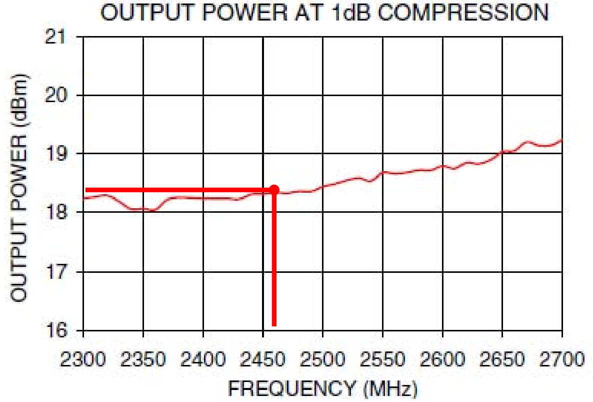
DC Power = .25 Watt

RF Power = 6 – 3.3 = 2.7 dBm

Amplifier



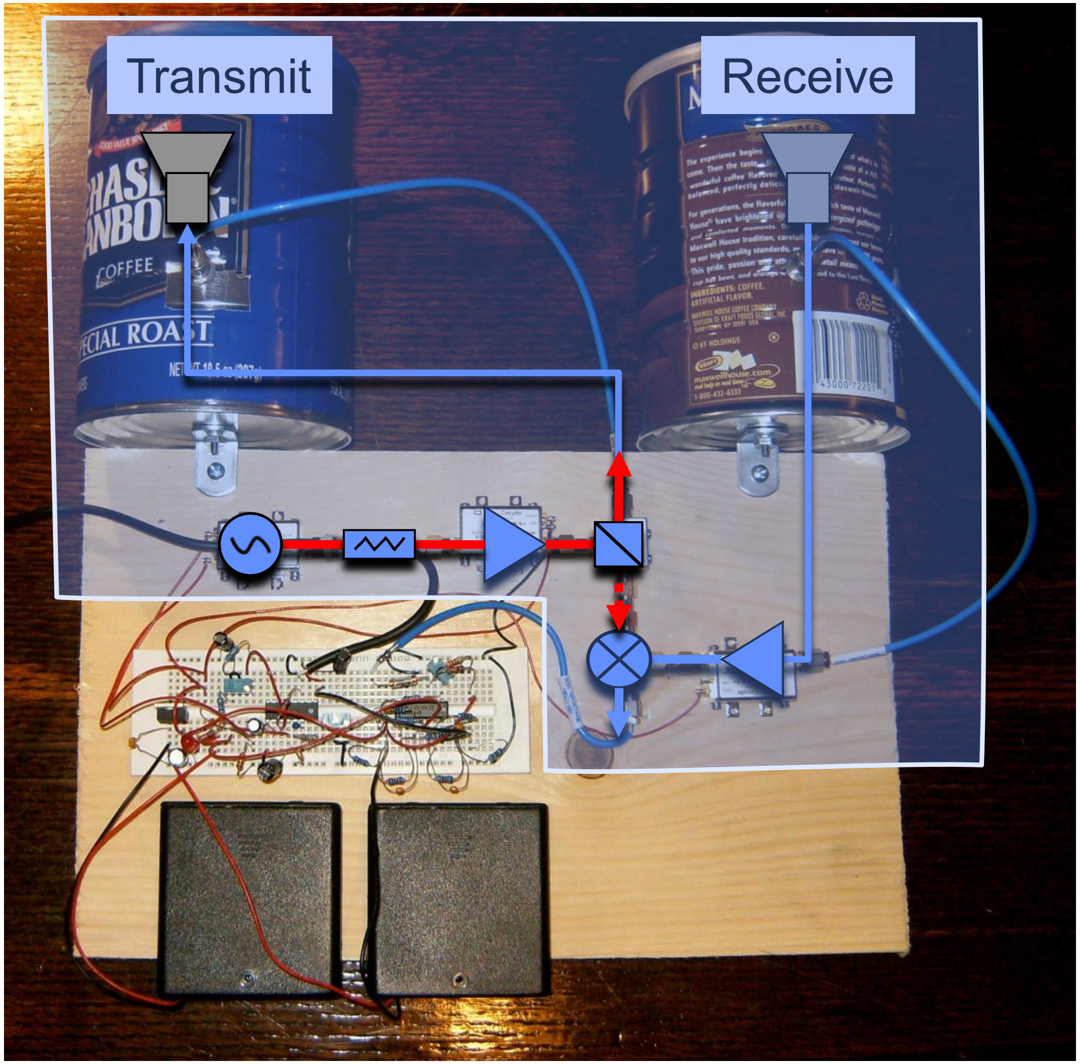


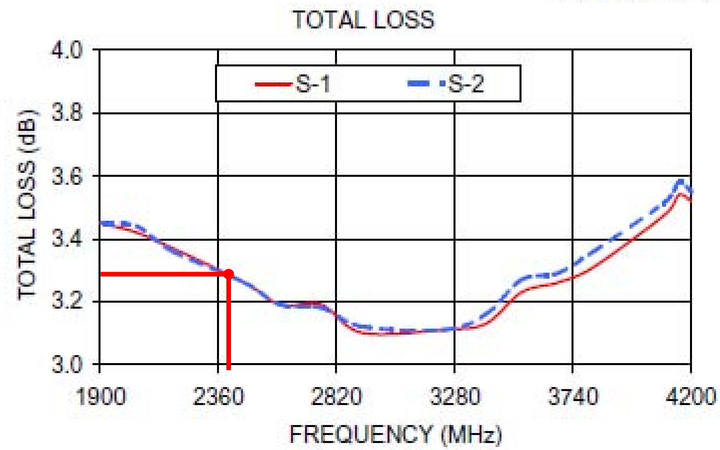


DC Power = .25 + .4 = .65 Watt

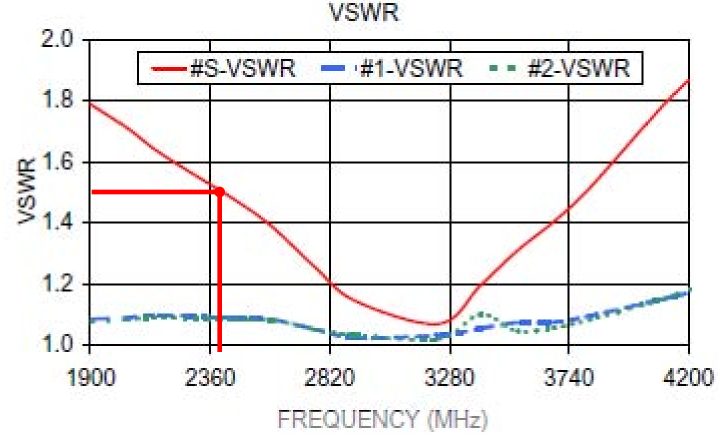
RF Power = 2.7 + 14 = 16.7 dBm

Splitter





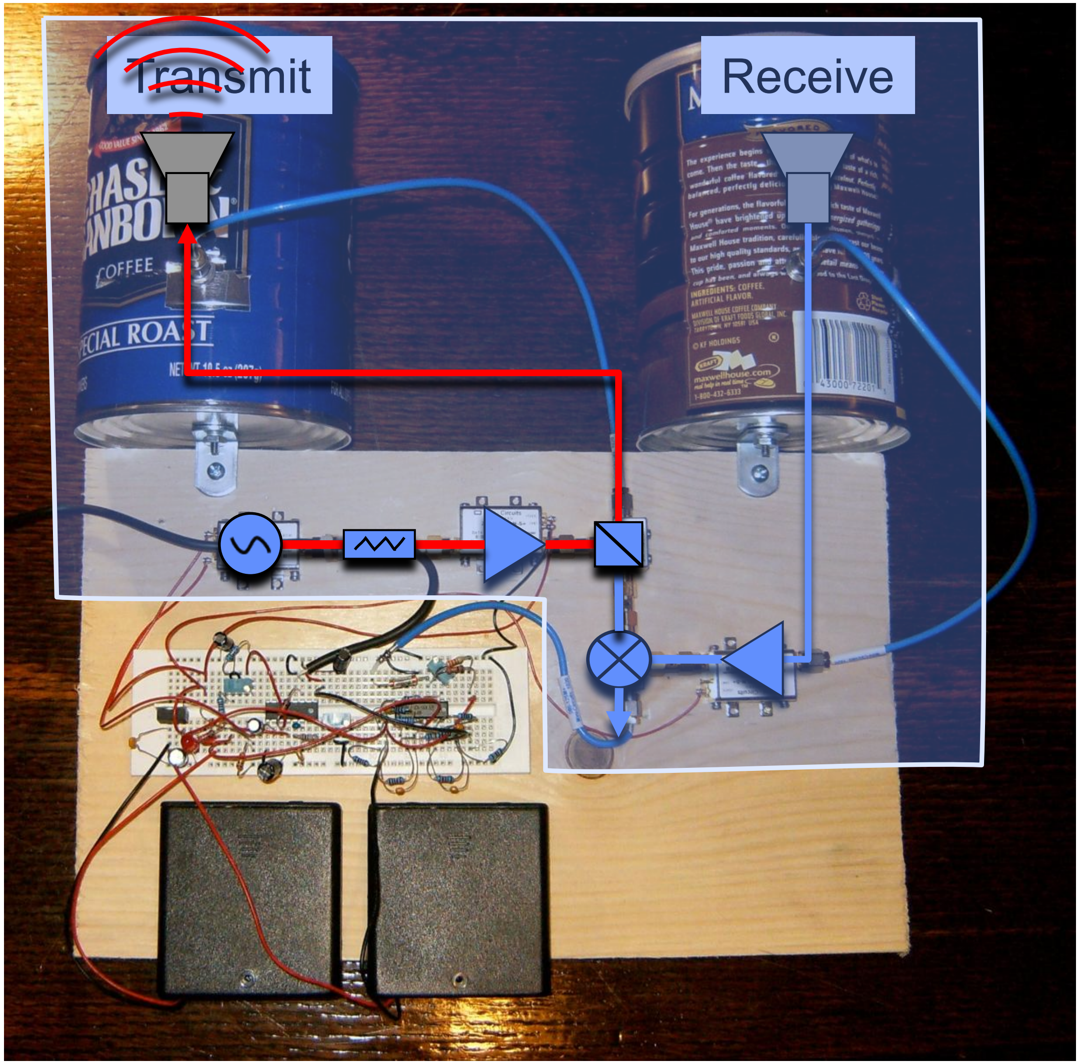
ZX10-2-42+

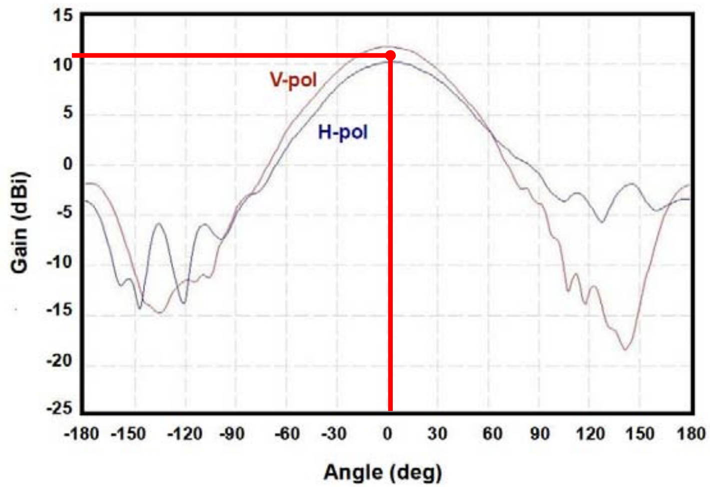


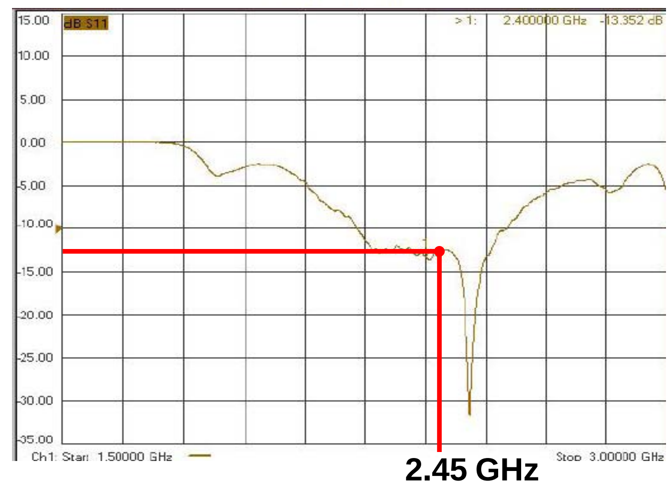
DC Power =.65 Watt

RF Power = 16.7 – 3.3 = 13.4 dBm

Antenna



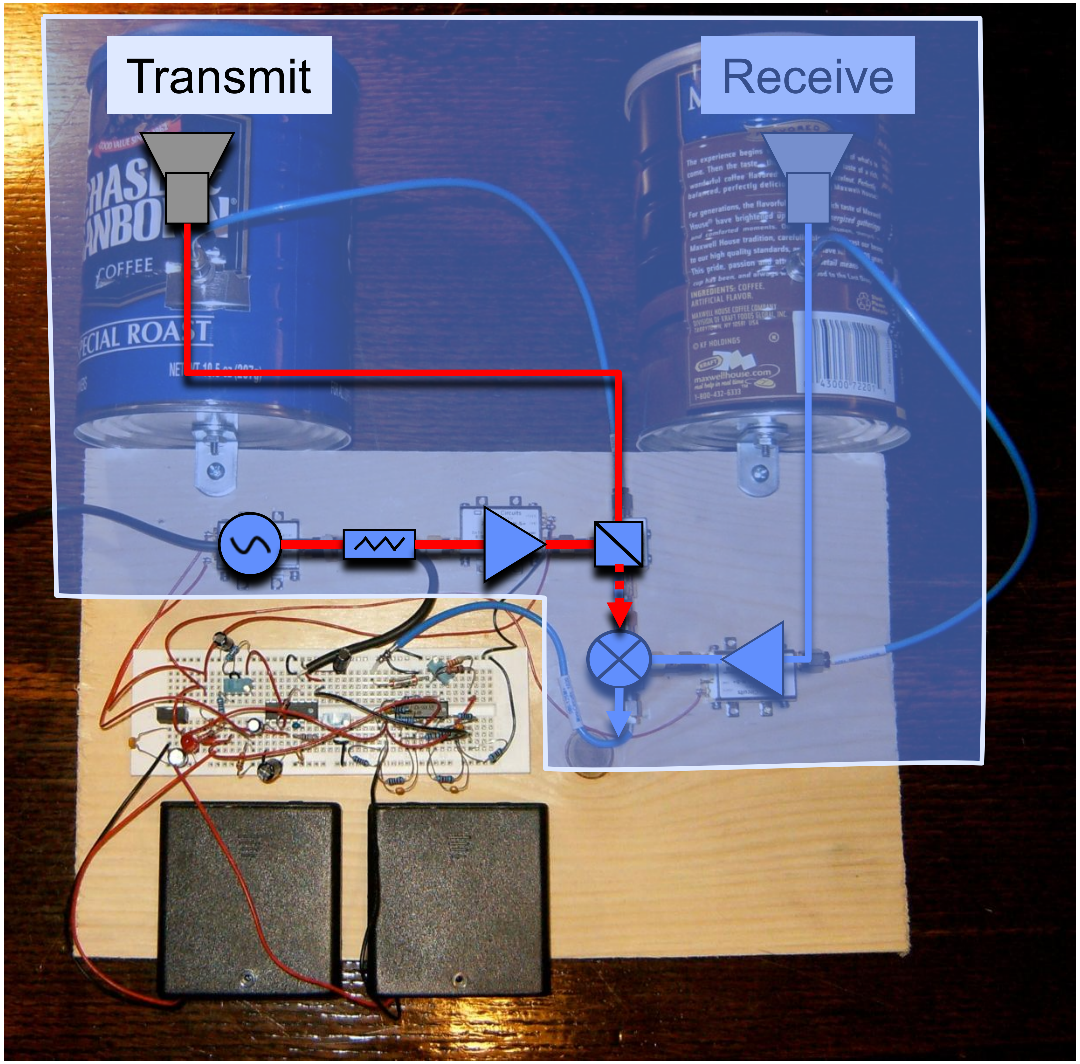




DC Power =.65 Watt

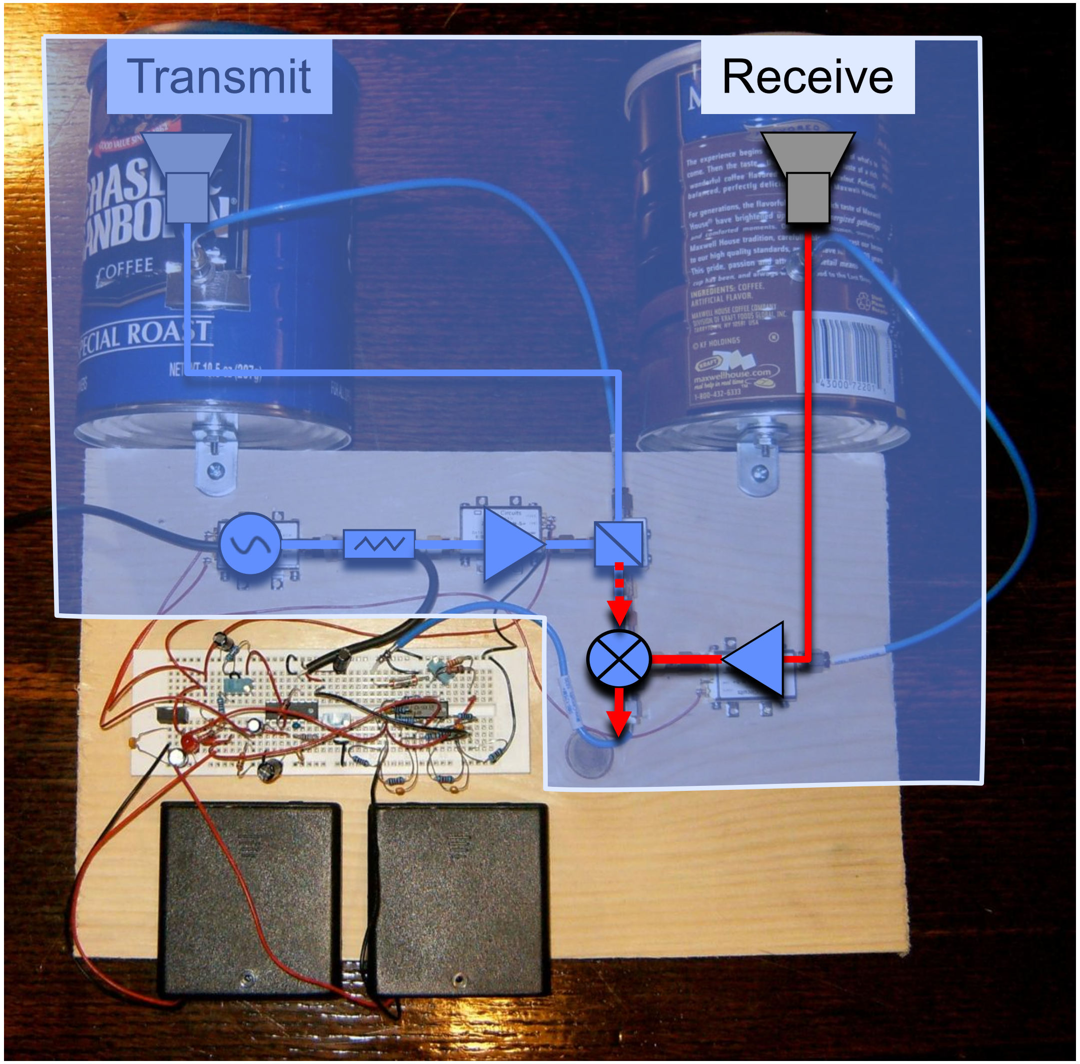
RF Power = 13.4 + 11 = 24.4 dBm EIRP

Transmit Chain Summary

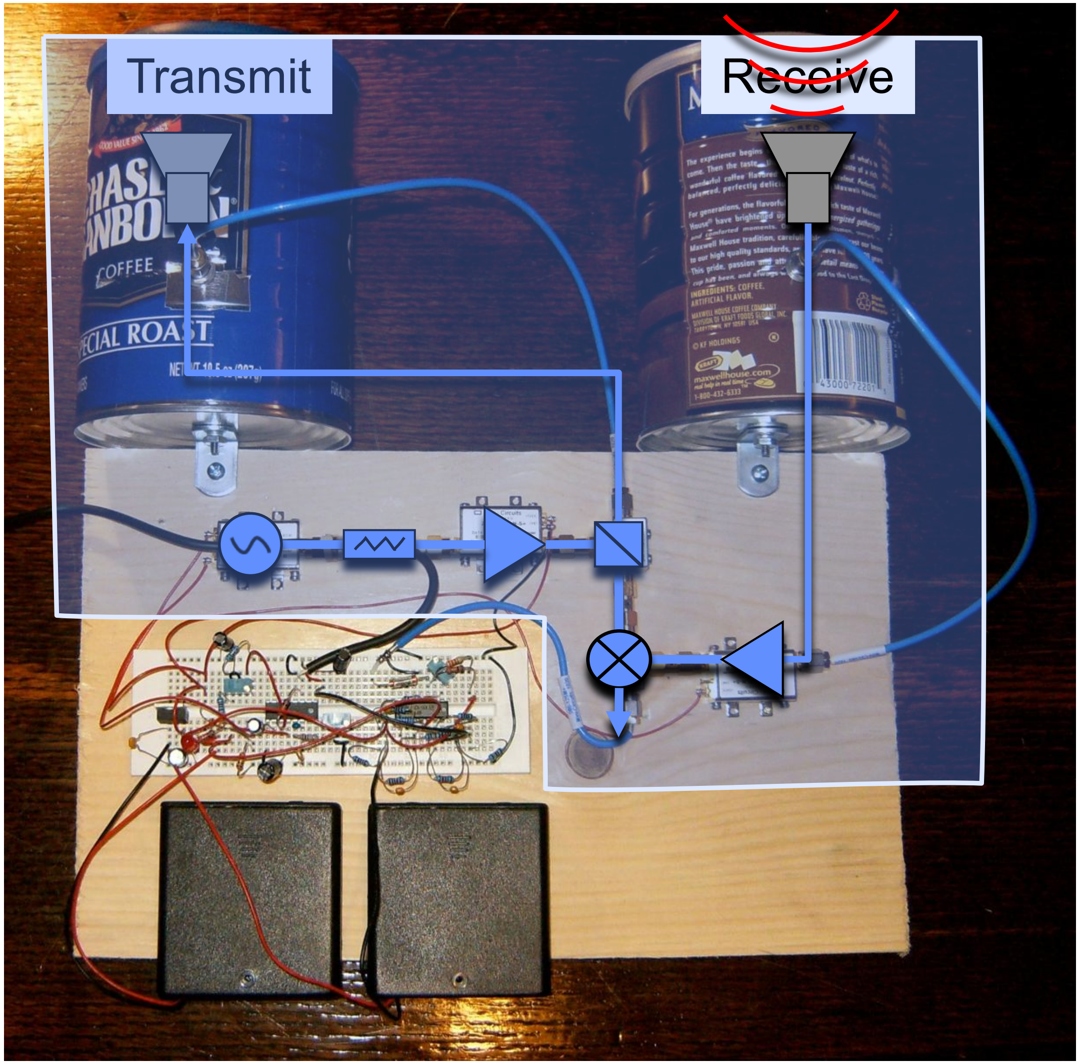


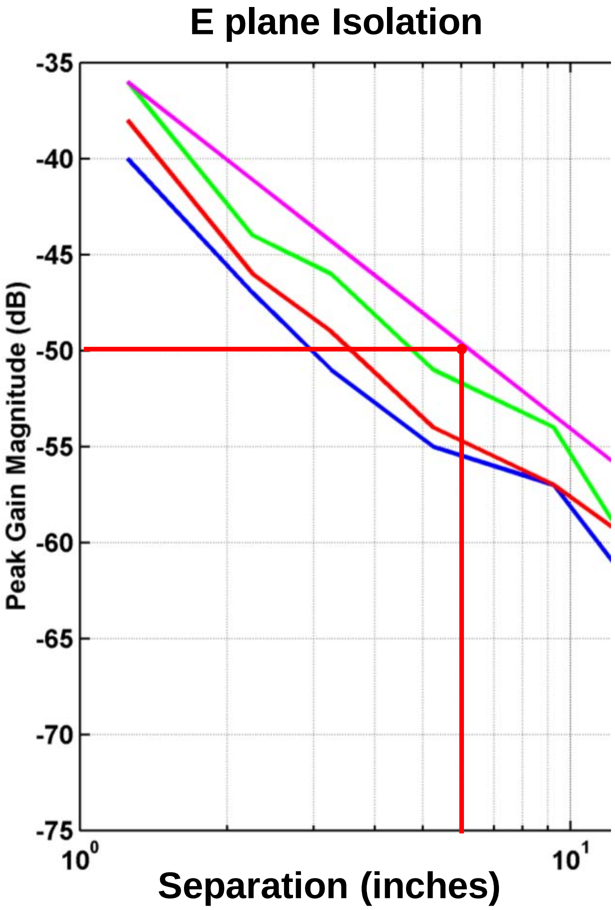
- DC Power = .65 Watt
- Tx Power = 24 dBm EIRP
- FCC ISM Req. < 1 Watt EIRP
- Provide copy of Tx waveform to receive chain (13dBm)

Receive Chain



Antenna

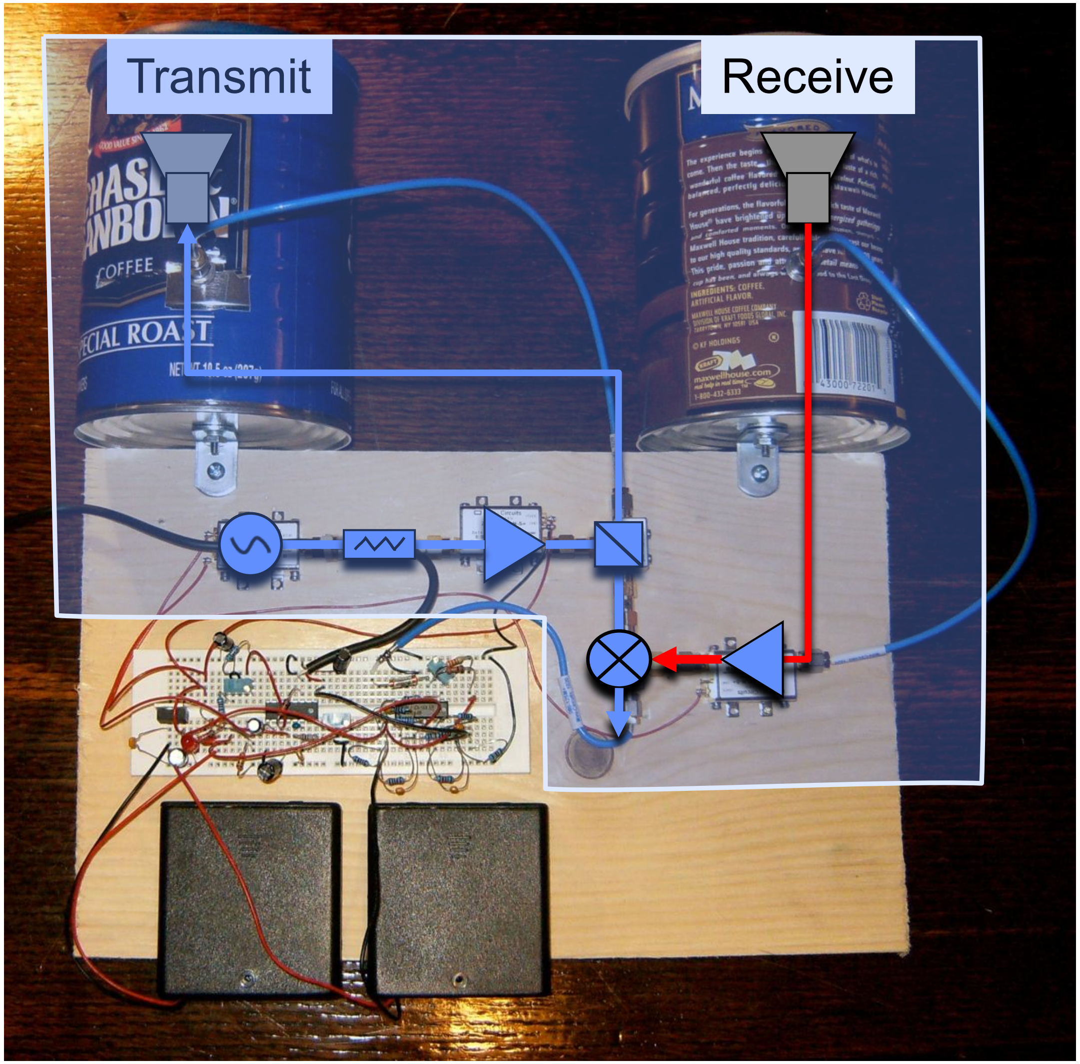


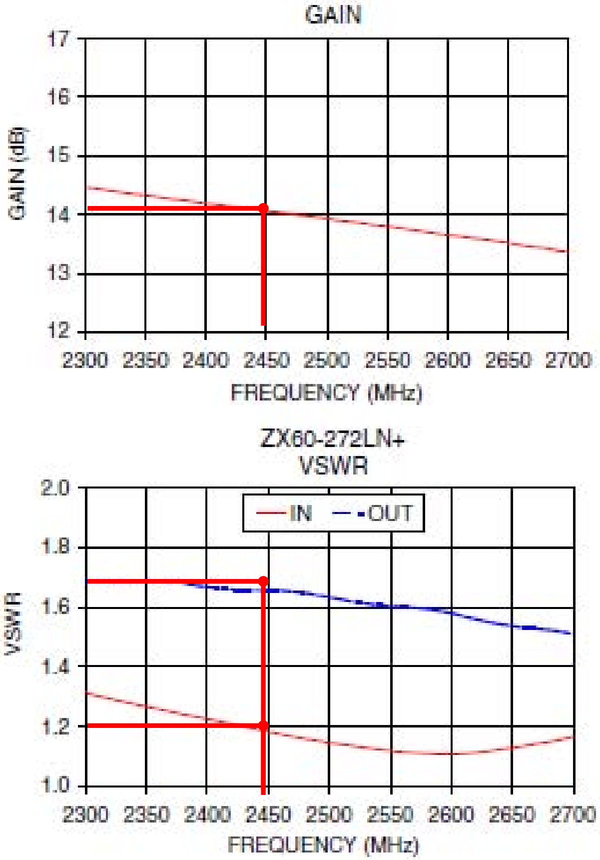


DC Power =.65 Watt

RF Power = 13.4 - 50 = -36.6 dBm

Amplifier

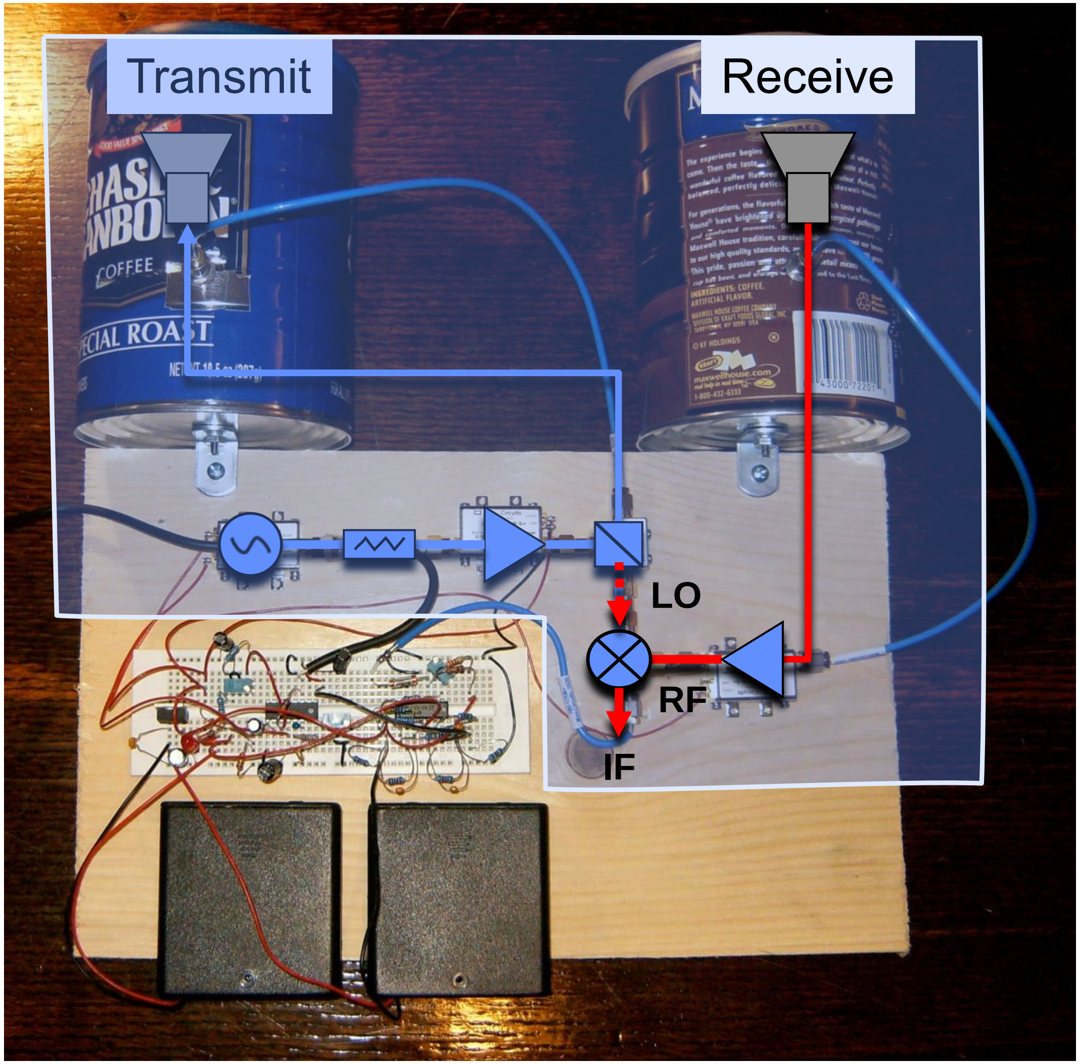


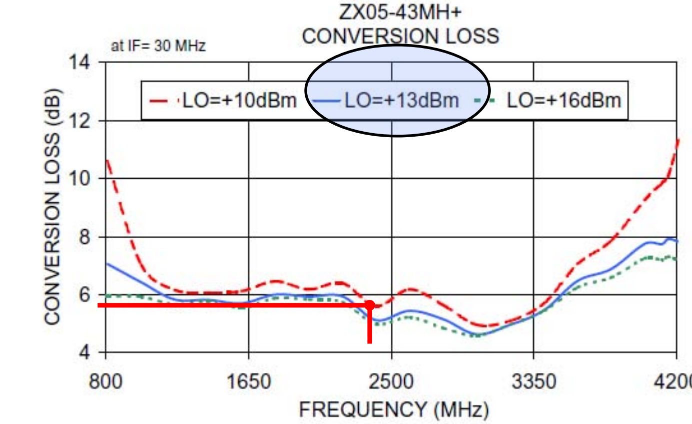


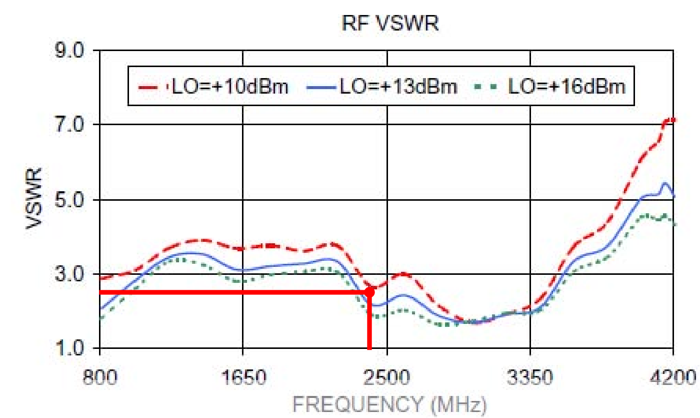
DC Power =.65 +.4 = 1 Watt

RF Power = -36.6 + 14 = -22.6 dBm

Mixer





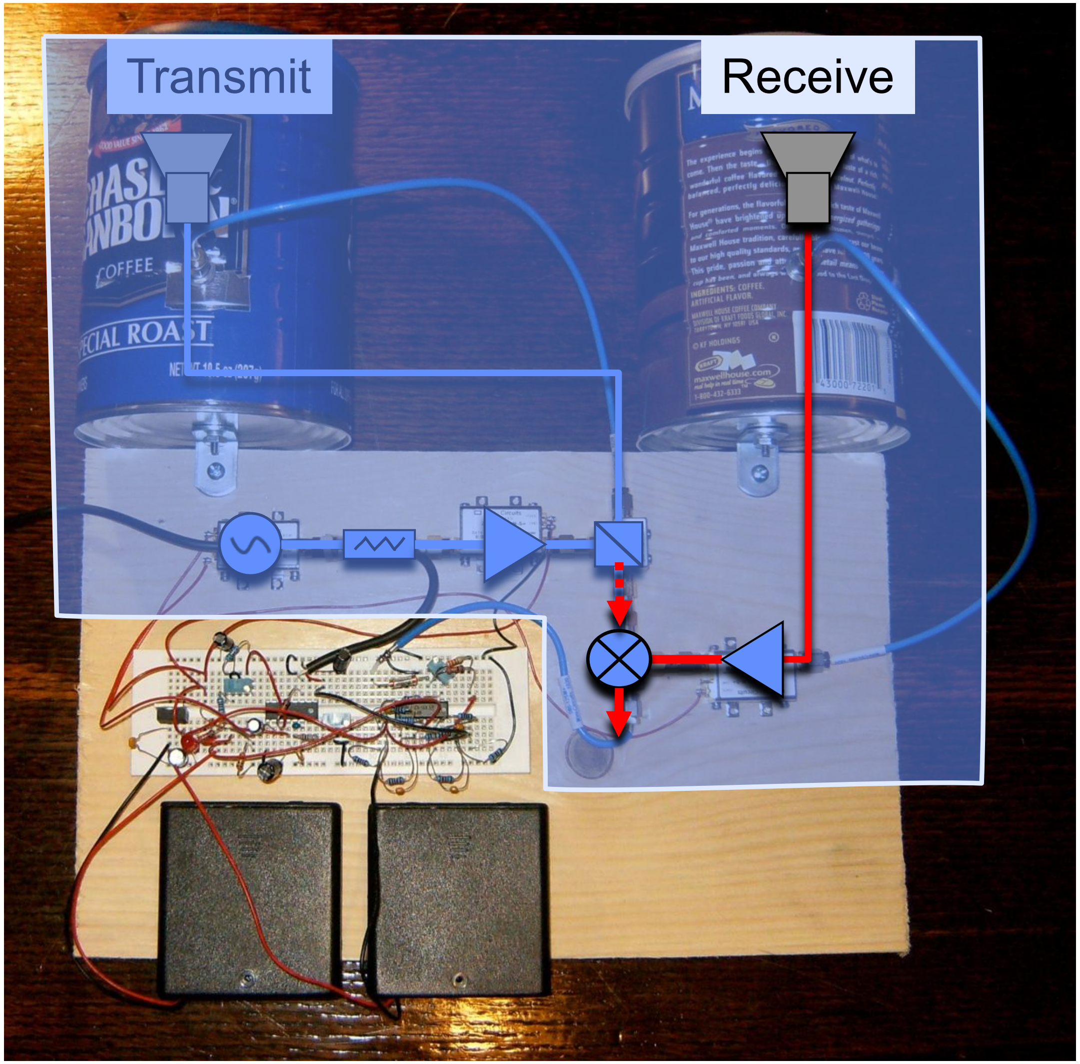


DC Power = 1 Watt

IF Power $_{RF}$ = -22.6 – 5.5 = -28.1 dBm

LO Leakage = 13 – 13 = 0 dBm

Receive Chain Summary



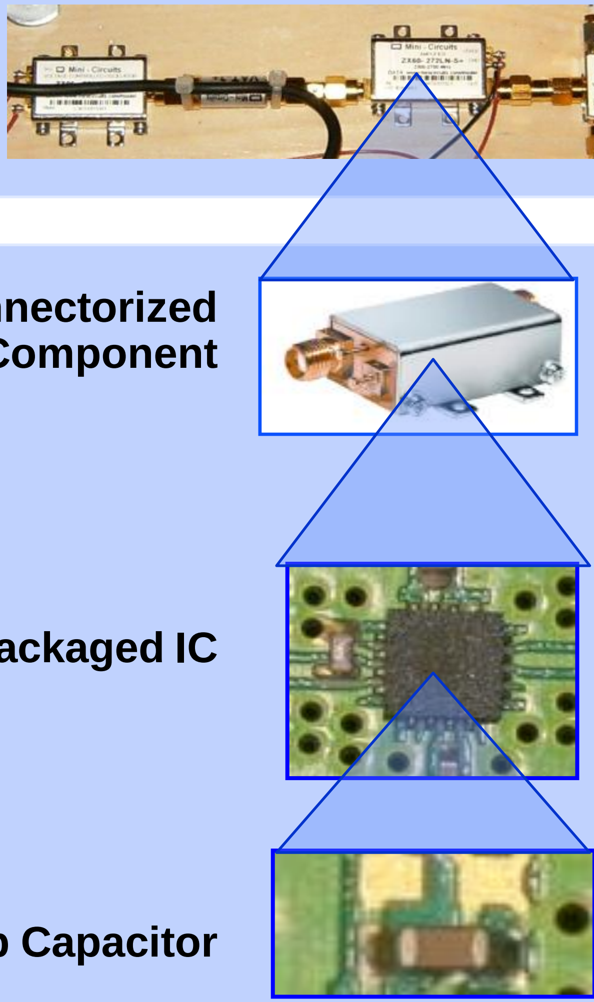
- DC Power = 1 Watt
- IF Power = -28 dBm
- Mixer uses copy of Tx waveform

Outline

- Introduction
- Circuit and Network Theory
- RF Measurements
- RF Design/Build
- **Summary**

Top Down Summary – System Concept

RF Component Chain

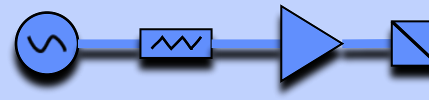


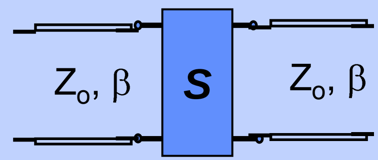
Connectorized Component

Packaged IC

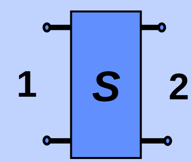
Chip Capacitor

Cascaded Two-Port Network Model

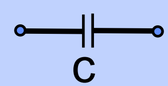




Two-Port with Transmission lines



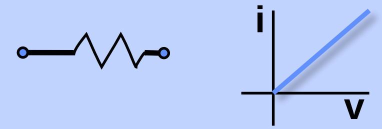
Two Port RF Component



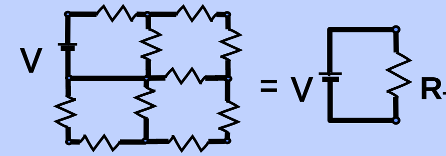
Circuit

Bottom-Up Summary
The Impedance Concept

Circuits

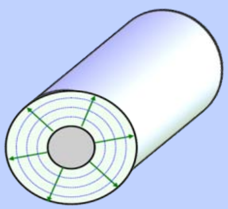


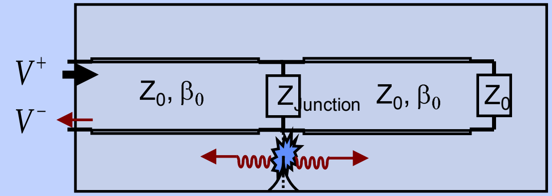
- Ohms Law, V=IR
- Complex impedance, models inductance and capacitance
- Circuit models form equivalent circuits



RF Components

- Transmission lines
- Scattering parameters
- Microwave and RF Networks





Systems

- Communications, Navigation, Radar…

Resource: Build a Small Radar System Capable of Sensing Range, Doppler, and Synthetic Aperture Radar Imaging
Dr. Gregory L. Charvat, Mr. Jonathan H. Williams, Dr. Alan J. Fenn, Dr. Steve Kogon, Dr. Jeffrey S. Herd