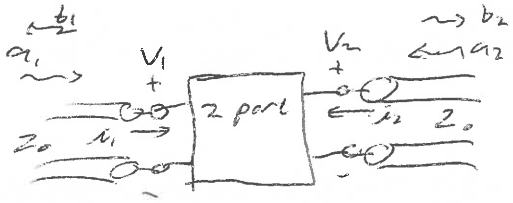
- Port I & V
- Power flow
  - ↳ complex power
  - ↳ Pin resistor
  - ↳ 2 port
- VNA operation
  - ↳ dir coupler
  - ↳ block
- VNA practicalities
  - ↳ open worse than short
  - ↳ phase ...
  - ↳ checks & cal
  - ↳ ref. plane

- Talking about S-parameters
  - ↳ type of 2 port parameters expressing how waves bounce off black box.
  - ↳ Contrast w/ Z-params ~ talk about voltages induced by currents



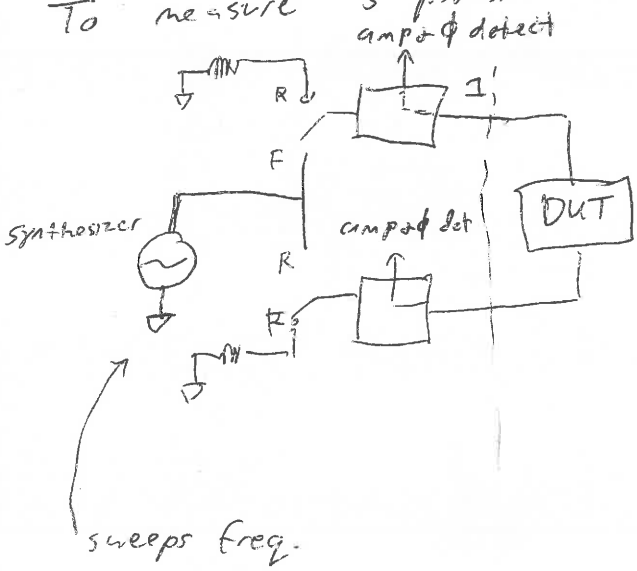
$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = Z \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \quad \text{vs.} \quad \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = S \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$\begin{bmatrix} V_{i1} \\ V_{i2} \end{bmatrix} / \sqrt{Z_0}$ $\quad$ $\begin{bmatrix} V_{i1} \\ V_{i2} \end{bmatrix} / \sqrt{Z_0}$

- measure by setting $i_1 = i_2 = 0$ (terminate w/ open)
- measure by terminating w/ Z_0 to kill b_1 or b_2

~ want to:
- figure out measurement techniques & interpretation
- relate to circuit calculations we already knew
- relate to power delivery

To measure S-params we use a Vector Network Analyzer



- Relies on directional couplers
  - ↳ split waves into fwd & rev components, more later
  - ↳ observe reflected waves on one & fwd. waves on other for direct S-param measure

- VNA only takes good measurements when calibrated
  - ↳ calibrate w/ cal. standards short, open, load, thru

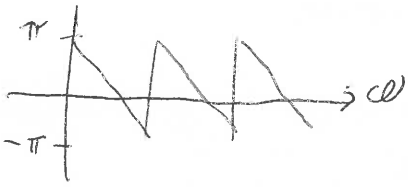
↳ short to find ref. plane

$$S_{VNA} = \begin{bmatrix} e^{j\beta z_1} & \\ & e^{j\beta z_2} \end{bmatrix} S_{DUT}$$

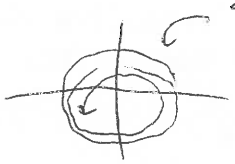
reference plane

- Need to define where $z=0$ is, i.e. measure z_1 & z_2
- O/w have a lot of excess phase: $\phi = \beta z_1 = \frac{2\pi}{\lambda} z_1 = \omega \cdot \frac{z_1}{v}$

will see phase plot



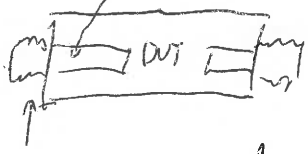
You guys - what will smith chart look like



arc parametrized in ω

- why not open? capacitance & radiation lead to worse results
- going on to PCB

extra φ on this t. line



short sets z=0 here

options: cal. in place
port extension

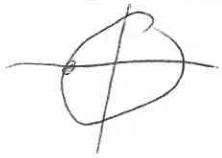
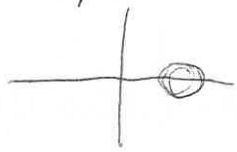
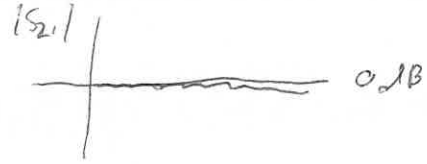
open & Load

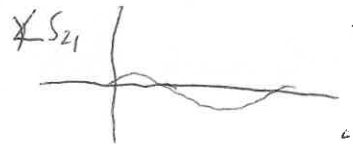
re-reflection fwd. leakage

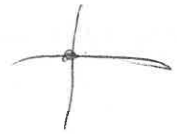
- source mismatch & directivity errors
- open is an independent reflection, load should be no reflection

thru

- frequency response of fixturing

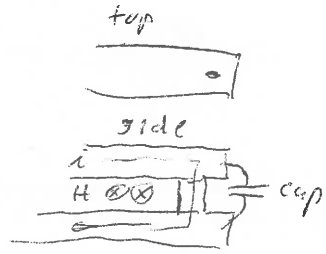
- post cal checks
  - short S11 or S22

  - open S11 or S22

    - Not as good b/c shunt cap
  - thru




- look @ delay too, nearly 0
- Hard to read over a few 100 MHz


- careful of port 2 connector protector
- only screw in turtle-neck so you don't break internal pins
- Debugging ~ check cables & connectors. Wiggle to find bad ones
  ~ sanity check ... am I seeing a signal?
- When to recalibrate → change in sweep of ω
  → change in fixturing

Notes on PCB parasitics
- via has inductance ~1 nH in series to gnd
- pad has cap
  - in shunt to gnd.



- Extract w/ VNA by making resonant
  ↳ @ resonance series → short & ∥ → open
  ↳ big phase change, magnitude changes, but reflects @ res <u>and</u> off res.

Can express port I & V in terms of S parameters
→ can invert to get screwy definition of a & b, beware!

$V_1 = V_{i1} + V_{r1} = \sqrt{Z_0}(a_1 + b_1)$

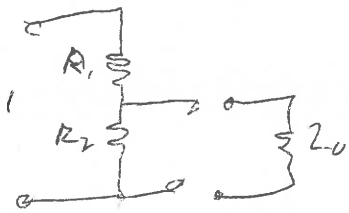
$I_1 = (V_{i1} - V_{r1})/Z_0 = \frac{a_1 - b_1}{\sqrt{Z_0}}$

$a_1 = \frac{V_1 + Z_0 I_1}{\sqrt{Z_0}}$ $\quad b_1 = \frac{V_1 - Z_0 I_1}{\sqrt{Z_0}}$

~~- Analytic power~~

- Relating S-params to ckts
  - S_{11} & S_{22} easy enough to calculate ~ reflection coeff w/ load on port

eg:



$$S_{11} = \frac{R_1 + R_2 \| Z_0 - Z_0}{R_1 + R_2 \| Z_0 + Z_0} \quad \& \quad S_{22} = \frac{R_2 \| (R_1 + Z_0) - Z_0}{R_2 \| (R_1 + Z_0) + Z_0}$$

- Get S_{21} & S_{12} from port voltage def$^{\underline{n}}$ of a_1 & b_1

- S_{21} & S_{12} a bit more involved, but can be calculated from Z params

$$S = (Z - Z_0 I)(Z + Z_0 I)^{-1} \quad \leftarrow \text{matrix form of } \Gamma$$

$$Z = (I - S)^{-1}(I + S) Z_0$$

↳ formulas for $S_{21} = \underbrace{\frac{2 Z_0 Z_{21}}{(Z_{11} + Z_0)(Z_{22} + Z_0) - Z_{12} Z_{21}}}_{\text{call this } \Delta}$ $\quad S_{12} = \frac{2 Z_0 Z_{12}}{\Delta}$

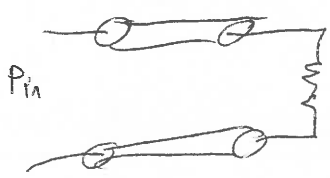
- Complex power
  - ↳ $P = \mathrm{Re}\{V I^*\}$ b/c we're representing sinusoidal V as $Ve^{j\omega t}$
  - ↳ Need voltage & current in phase to have power eg: Z_{load} fwd

- Power in wave is $\frac{1}{2}|a|^2$ & power into 2 port is $\frac{1}{2}|a|^2 - \frac{1}{2}|b|^2 = \mathrm{Re}\{V I^*\}$

$$\left\{ \frac{|V_{i1}|^2}{2 Z_0} \right.$$

- Lossy 2 ports won't send all their power out in b_2 ⇝ Hermitian matrices

eg: 1port



$P_{reflected} = |\Gamma|^2 P_{in}$

$P_{load} = (1 - |\Gamma|^2) P_{in}$

- more to come re: S_{21}

Filters next time b/c lab 3