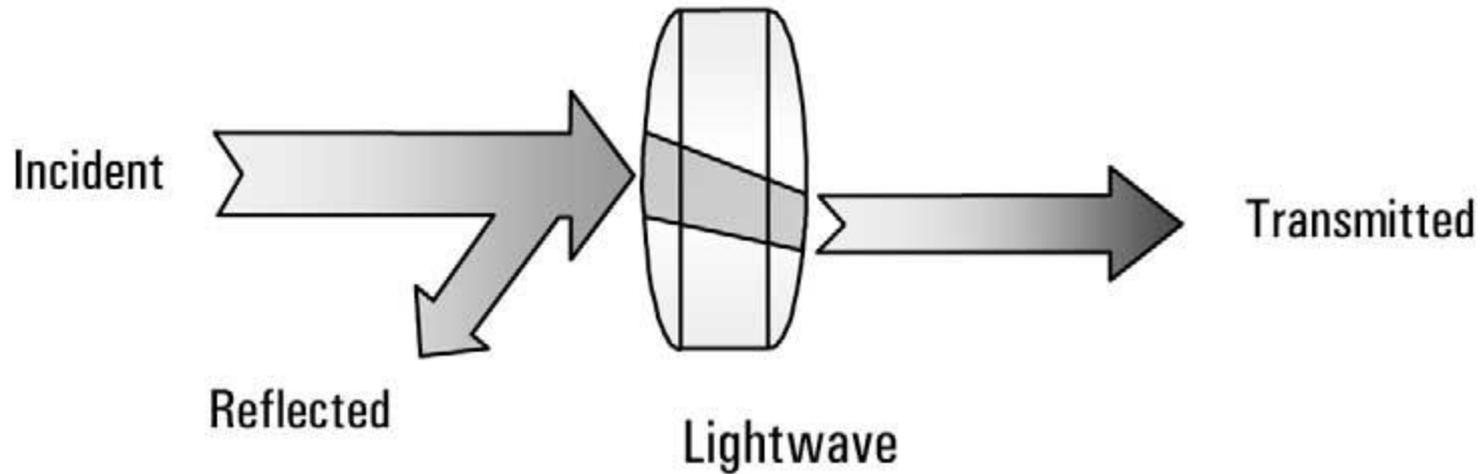


Vector Network Analysis

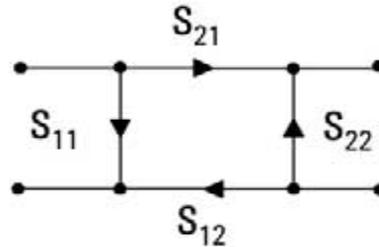
Basics (from Agilent)

Light-wave analogy

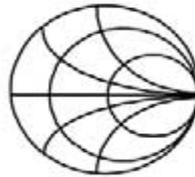


Need for both magnitude and phase

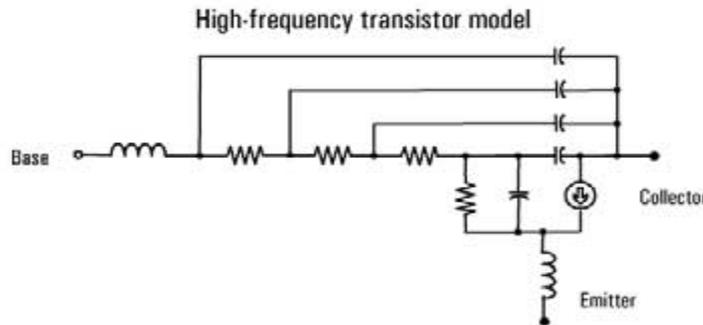
1. Complete characterization of linear networks



2. Complex impedance needed to design matching circuits



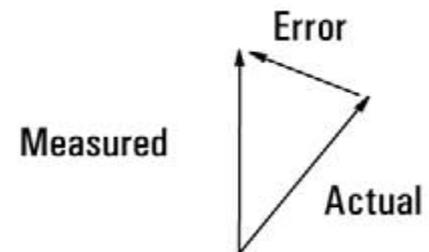
3. Complex values needed for device modeling



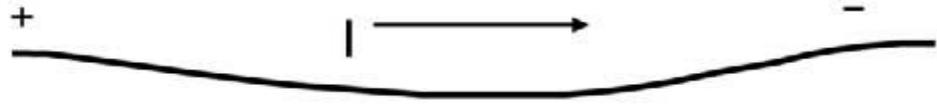
4. Time-domain characterization



5. Vector-error correction

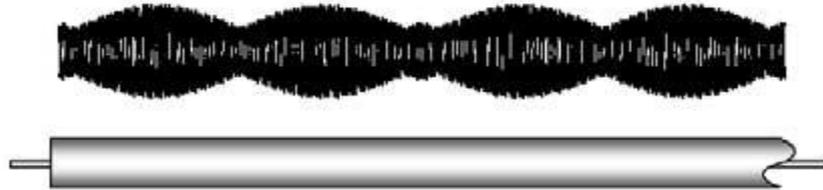


Transmission Line Basics



Low frequencies

- wavelengths \gg wire length
- current (I) travels down wires easily for efficient power transmission
- measured voltage and current not dependent on position along wire

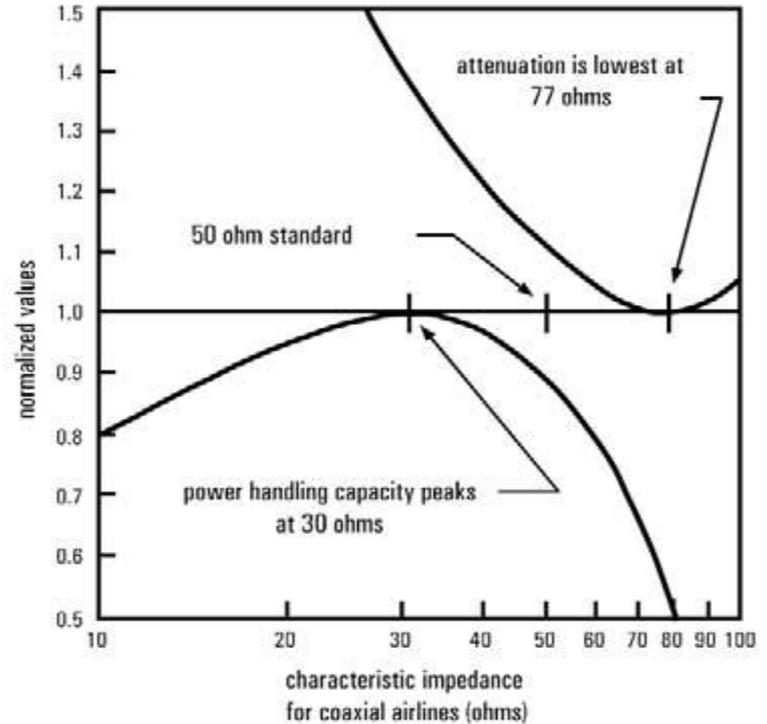
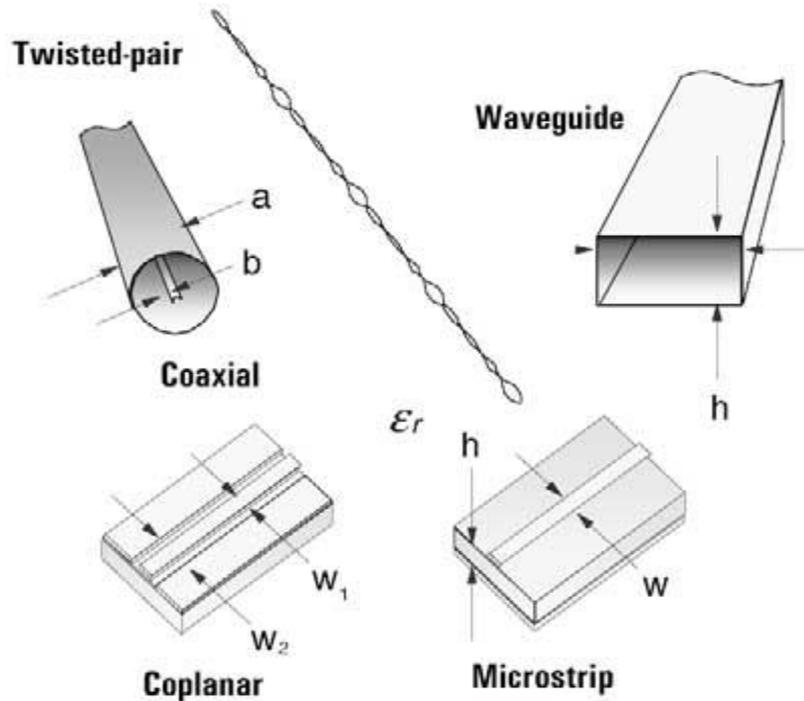


High frequencies

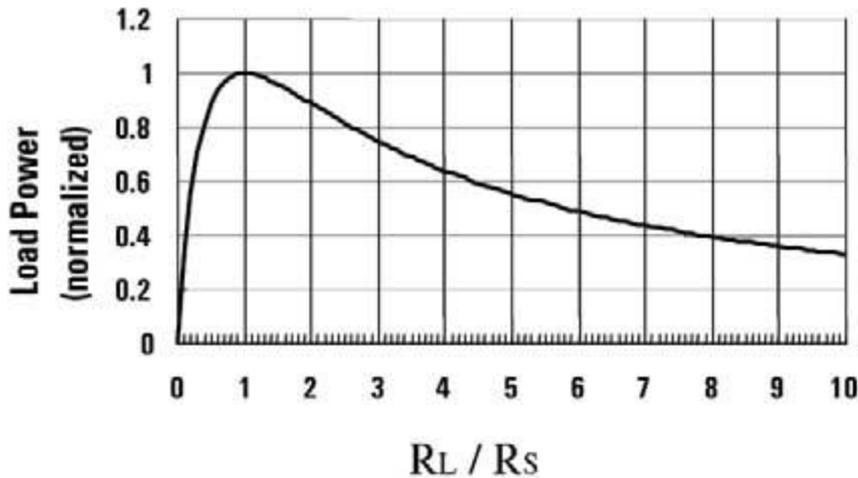
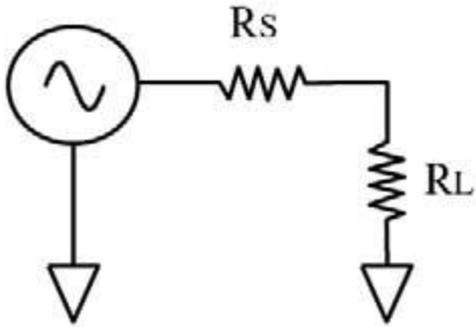
- wavelength \approx or \ll length of transmission medium
- need transmission lines for efficient power transmission
- matching to characteristic impedance (Z_0) is very important for low reflection and maximum power transfer
- measured envelope voltage dependent on position along line

Characteristic Impedance

- Z_0 determines relationship between voltage and current waves
- Z_0 is a function of physical dimensions and ϵ_r
- Z_0 is usually a real impedance (e.g. 50 or 75 ohms)

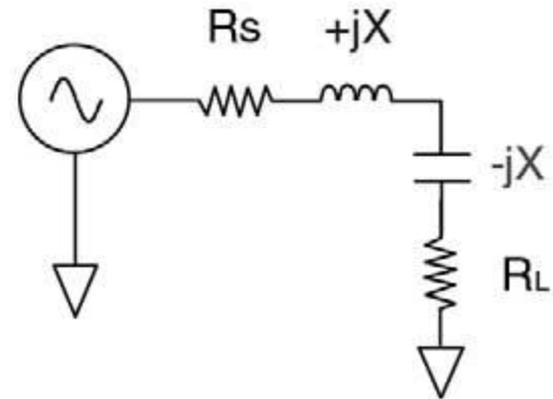


Power Transfer Efficiency



Maximum power is transferred when $R_L = R_S$

For complex impedances, maximum power transfer occurs when $Z_L = Z_s^*$ (conjugate match)

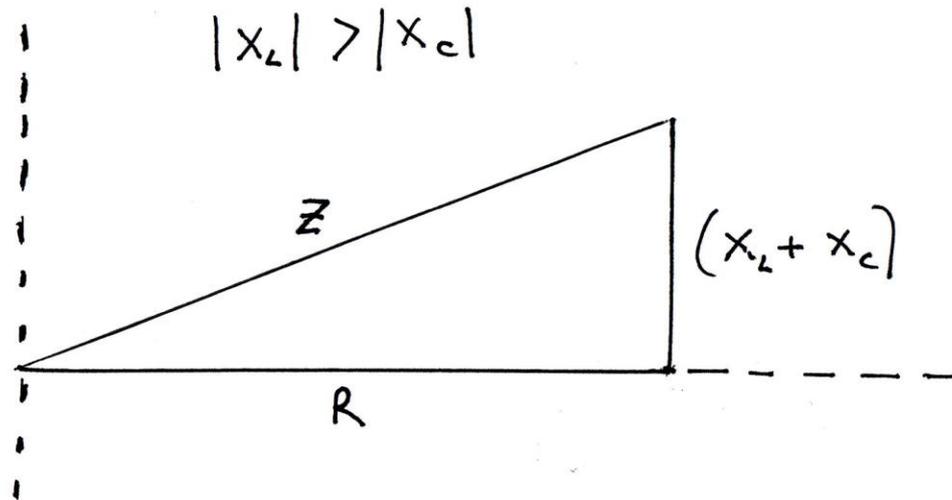


Review of Some Basic Relationships

$$Z = R + j(X_L + X_C) \quad \text{Note: vector addition}$$

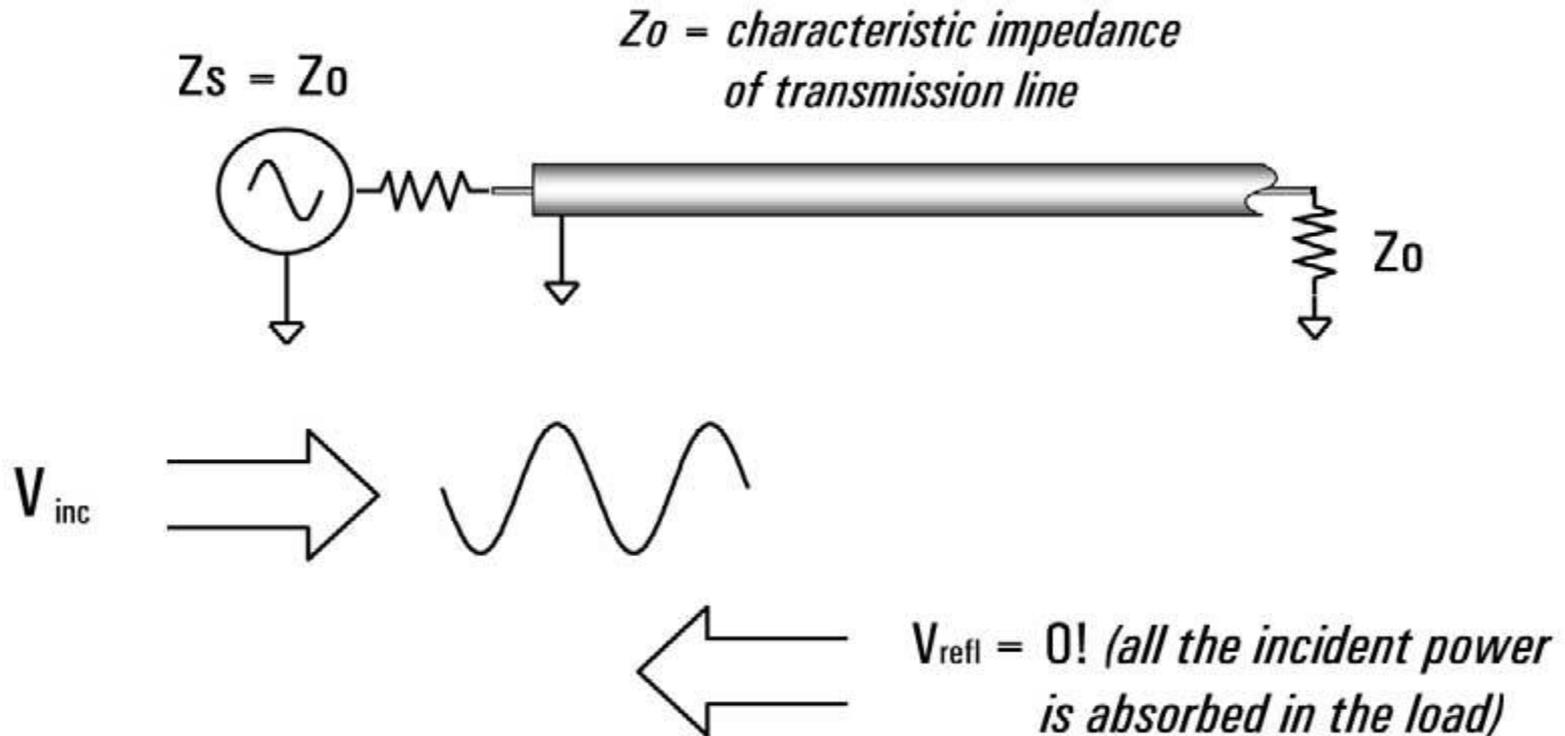
where $X_L = 2\pi fL$, $X_C = -1/2\pi fC$ Note X_C is negative

When $(X_L + X_C) = 0$, then $f = 1/2\pi \text{sq. root.}(LC)$



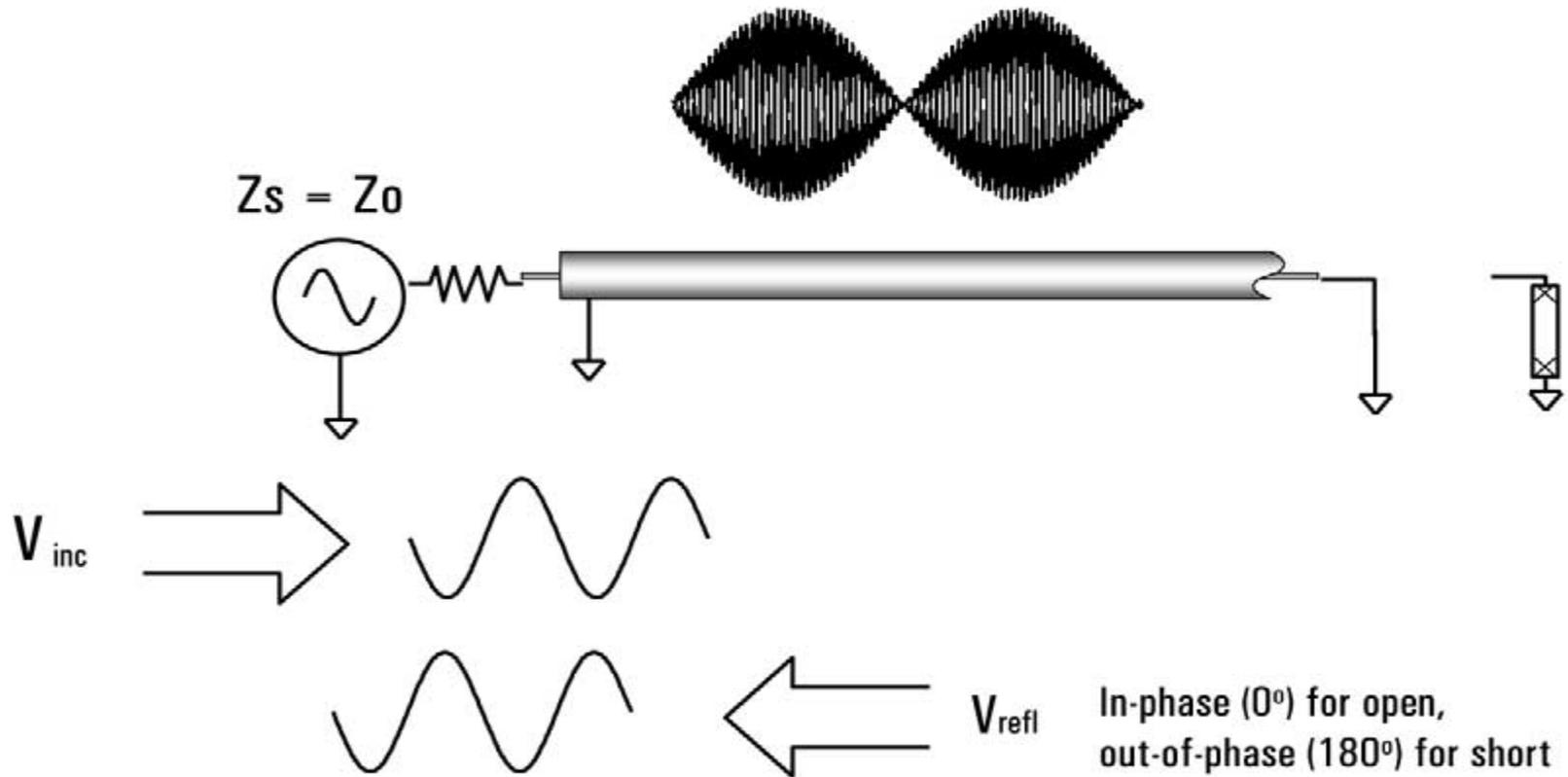
$$|Z| = \text{sq. root } [R^2 + (X_L + X_C)^2]$$

Termination Impedance = Z_0



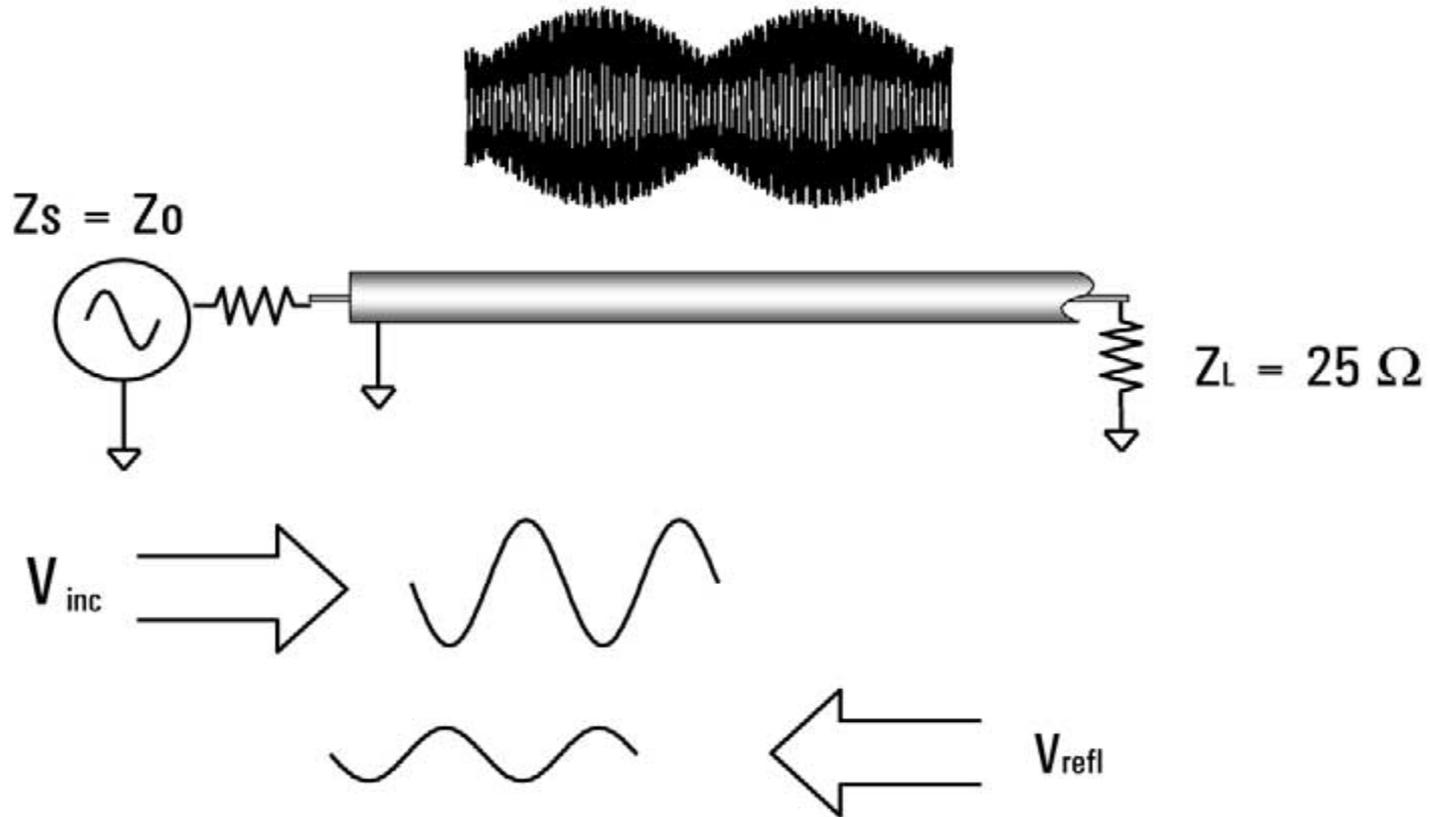
For reflection, a transmission line terminated in Z_0 behaves like an infinitely long transmission line

Termination Short, Open



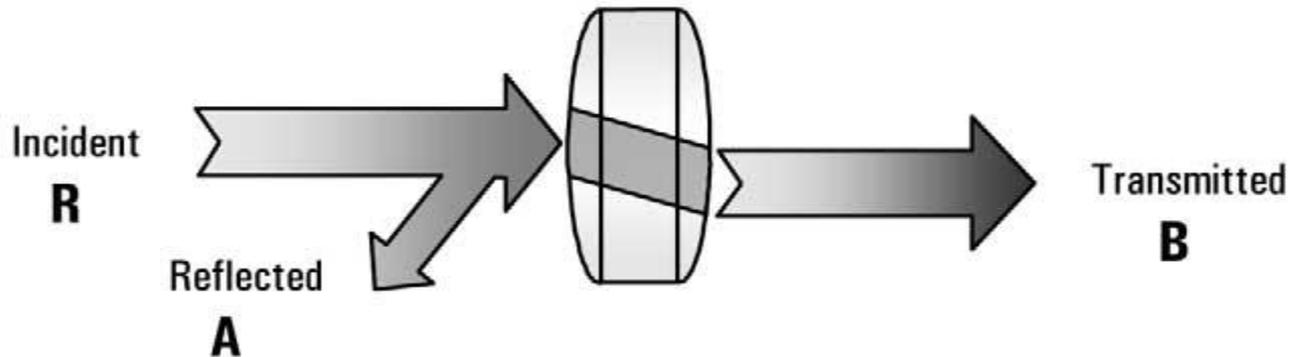
For reflection, a transmission line terminated in a short or open reflects all power back to source

Termination 25 Ω



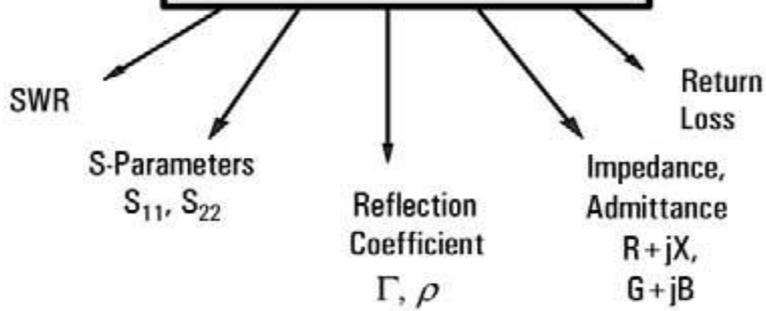
Standing wave pattern does not go to zero as with short or open

High-freq. Device Characterization



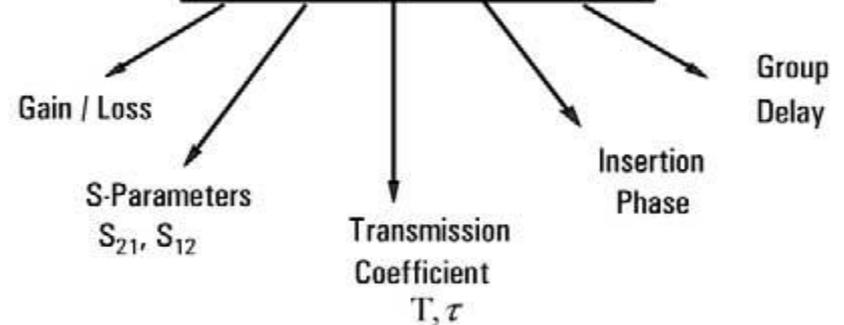
REFLECTION

$$\frac{\text{Reflected}}{\text{Incident}} = \frac{A}{R}$$



TRANSMISSION

$$\frac{\text{Transmitted}}{\text{Incident}} = \frac{B}{R}$$



Reflection Parameters

Reflection Coefficient

$$\Gamma = \frac{V_{\text{reflected}}}{V_{\text{incident}}} = \rho \angle \Phi = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Return loss = $-20 \log(\rho)$, $\rho = |\Gamma|$



Voltage Standing Wave Ratio

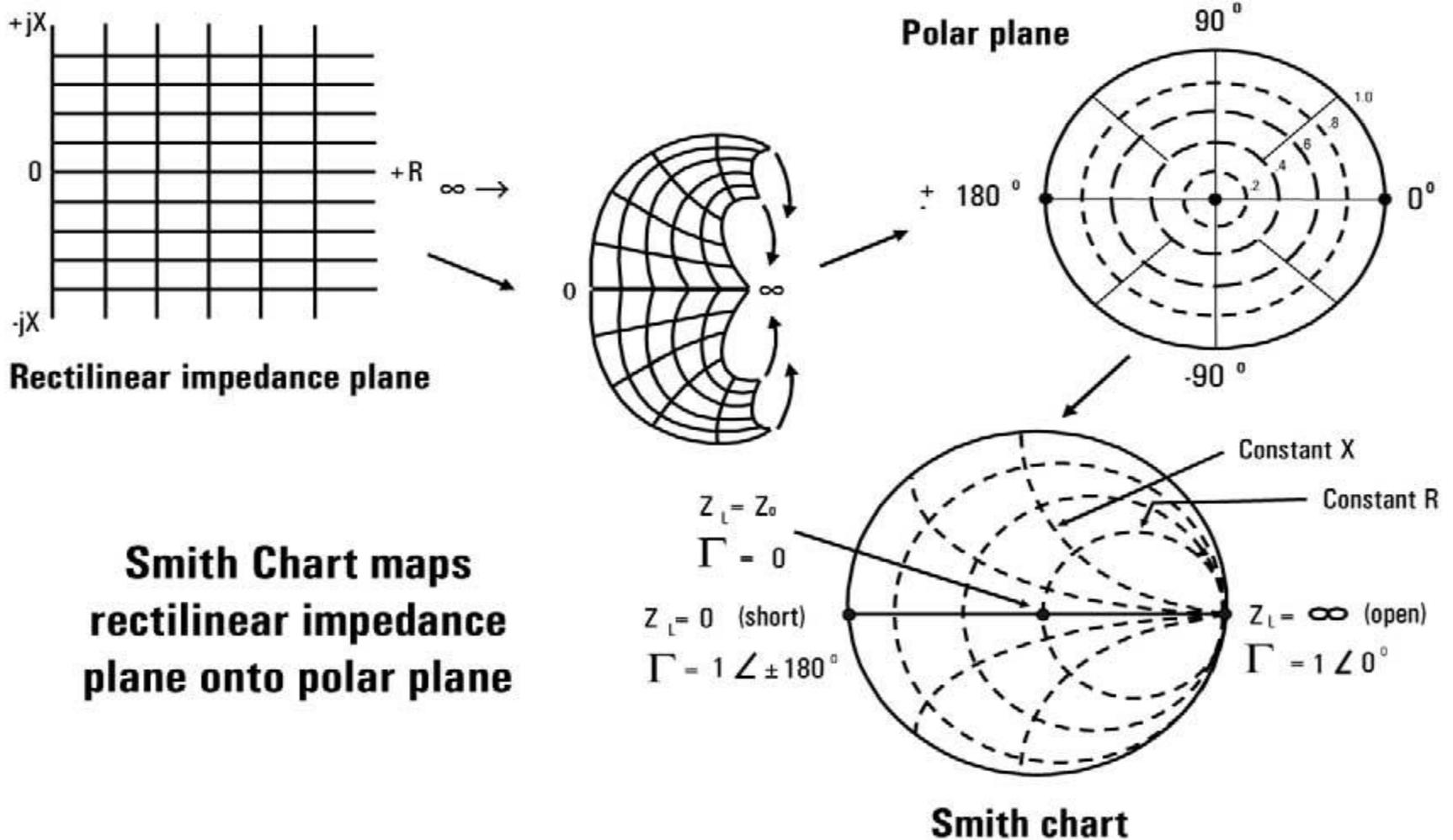
$$\text{VSWR} = \frac{E_{\text{max}}}{E_{\text{min}}} = \frac{1 + \rho}{1 - \rho}$$

No reflection
($Z_L = Z_0$)

Full reflection
($Z_L = \text{open, short}$)

0	ρ	1
∞ dB	RL	0 dB
1	VSWR	∞

Graphical Representation



**Smith Chart maps
rectilinear impedance
plane onto polar plane**

Transmission Parameters

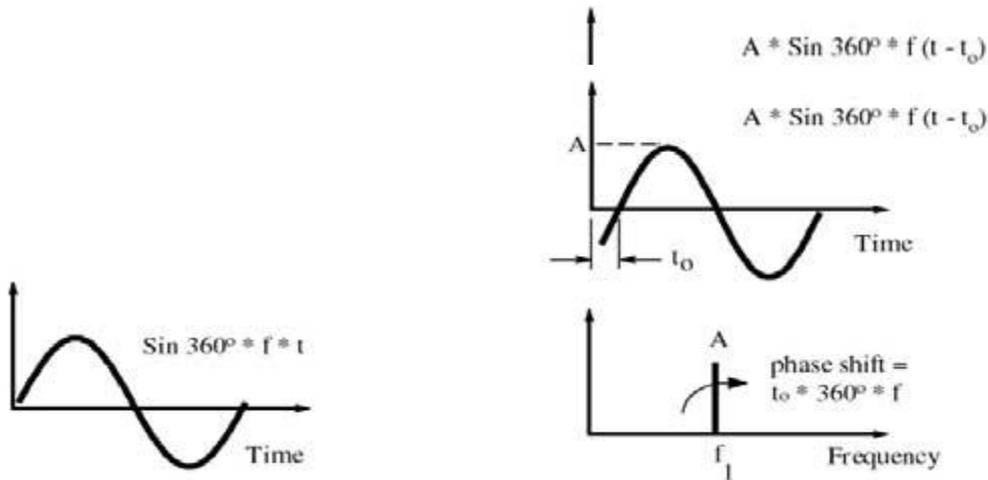


$$\text{Transmission Coefficient} = T = \frac{V_{\text{Transmitted}}}{V_{\text{Incident}}} = \tau \angle \phi$$

$$\text{Insertion Loss (dB)} = -20 \text{ Log} \left| \frac{V_{\text{Trans}}}{V_{\text{Inc}}} \right| = -20 \log \tau$$

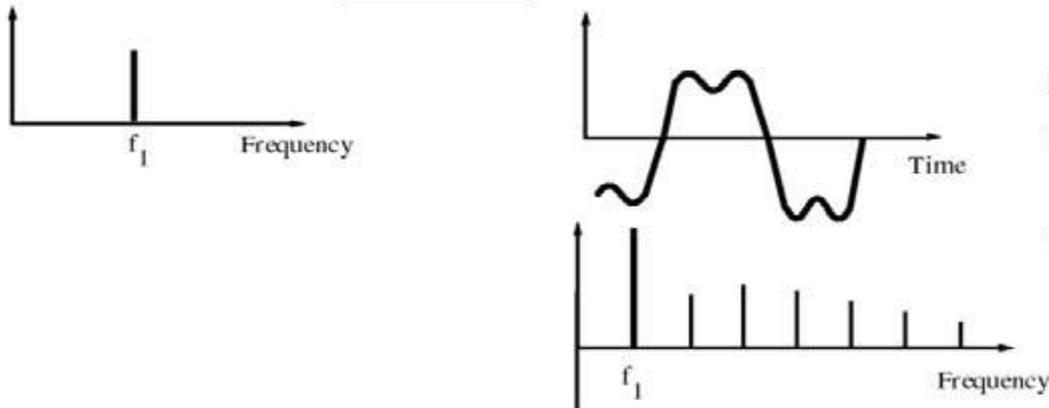
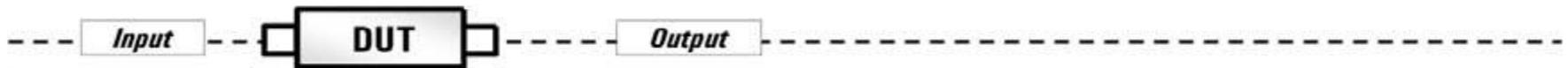
$$\text{Gain (dB)} = 20 \text{ Log} \left| \frac{V_{\text{Trans}}}{V_{\text{Inc}}} \right| = 20 \log \tau$$

Linear vs. Non-linear Behavior



Linear behavior:

- input and output frequencies are the same (no additional frequencies created)
- output frequency only undergoes magnitude and phase change

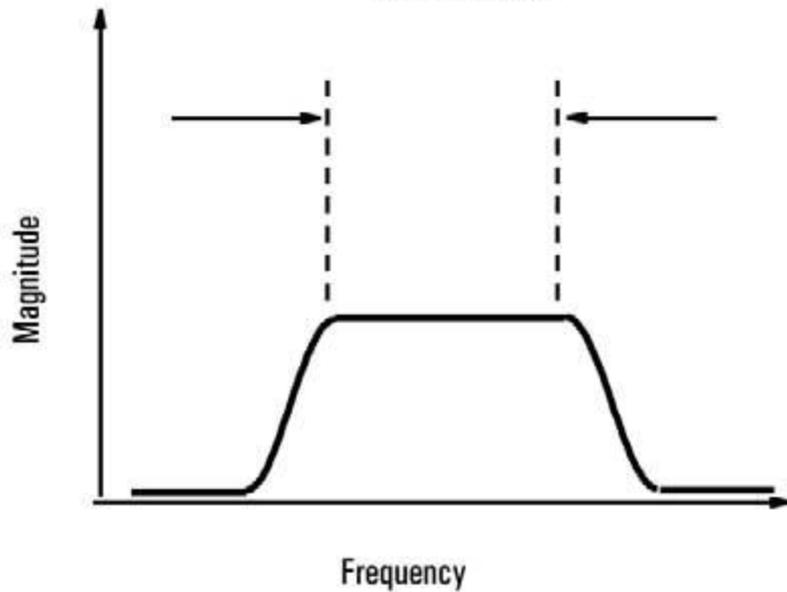


Nonlinear behavior:

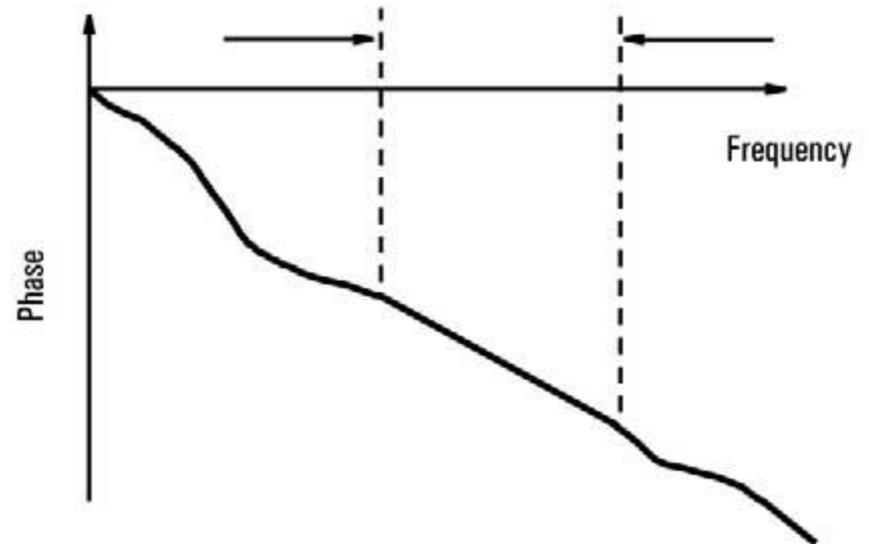
- output frequency may undergo frequency shift (e.g. with mixers)
- additional frequencies created (harmonics, intermodulation)

Linear Networks

Constant amplitude over bandwidth of interest

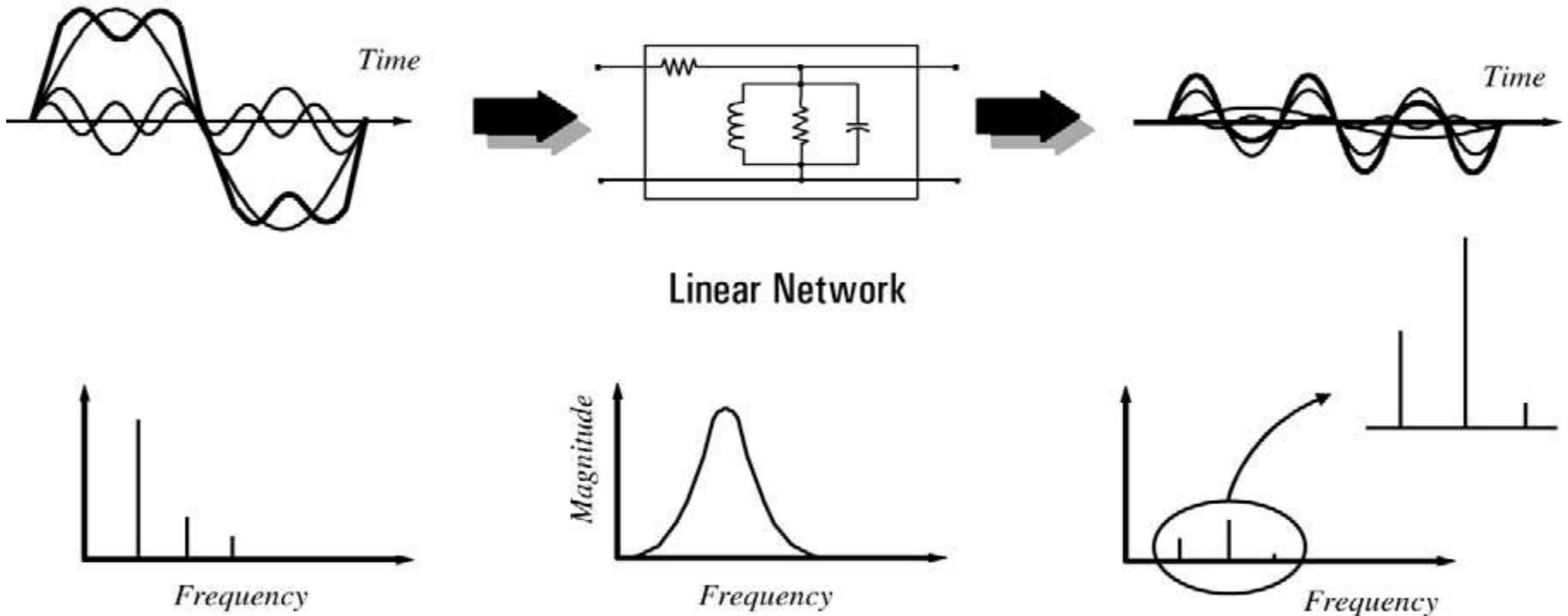


Linear phase over bandwidth of interest



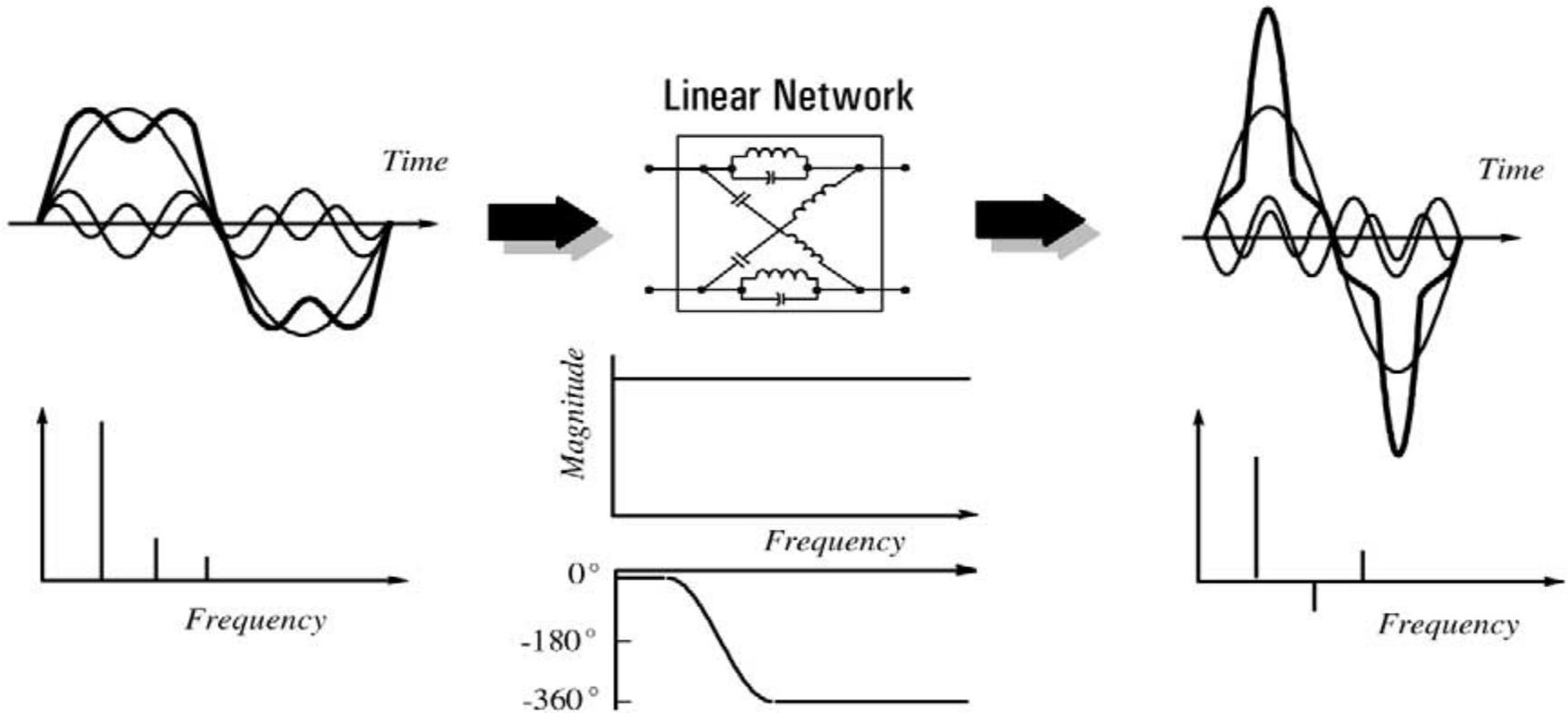
Magnitude Varies with Frequency

$$F(t) = \sin \omega t + \frac{1}{3} \sin 3\omega t + \frac{1}{5} \sin 5\omega t$$

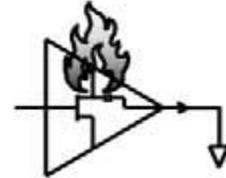


Phase Varies with Frequency

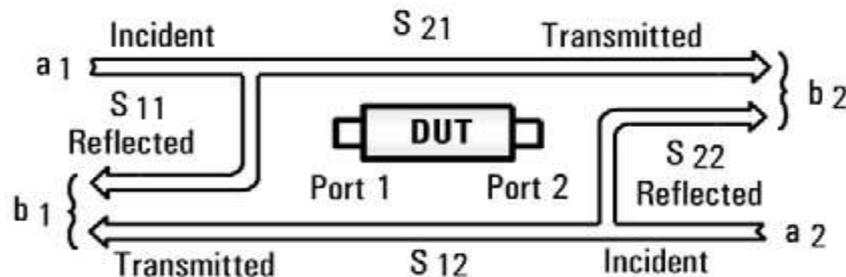
$$F(t) = \sin \omega t + \frac{1}{3} \sin 3\omega t + \frac{1}{5} \sin 5\omega t$$



Why Use S-parameters ?



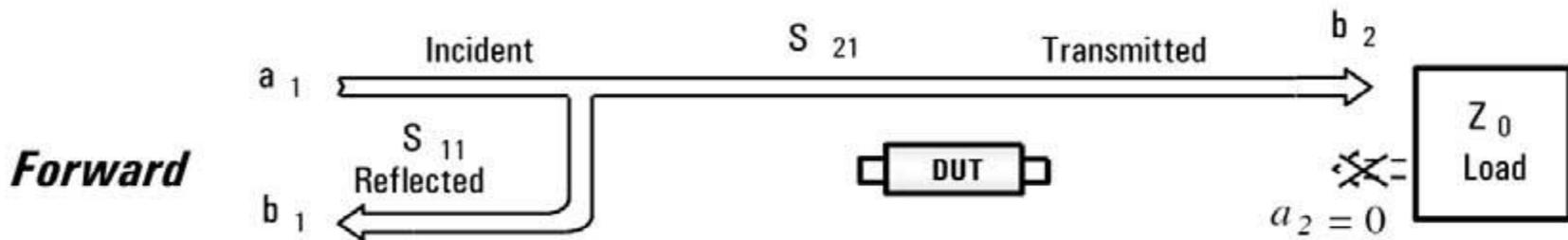
- relatively easy to **obtain** at high frequencies
 - measure voltage traveling waves with a vector network analyzer
 - don't need shorts/opens which can cause active devices to oscillate or self-destruct
- relate to **familiar** measurements (gain, loss, reflection coefficient ...)
- can **cascade** S-parameters of multiple devices to predict system performance
- can **compute** H, Y, or Z parameters from S-parameters if desired
- can easily import and use S-parameter files in our **electronic-simulation** tools



$$b_1 = S_{11} a_1 + S_{12} a_2$$

$$b_2 = S_{21} a_1 + S_{22} a_2$$

Measuring S-parameters

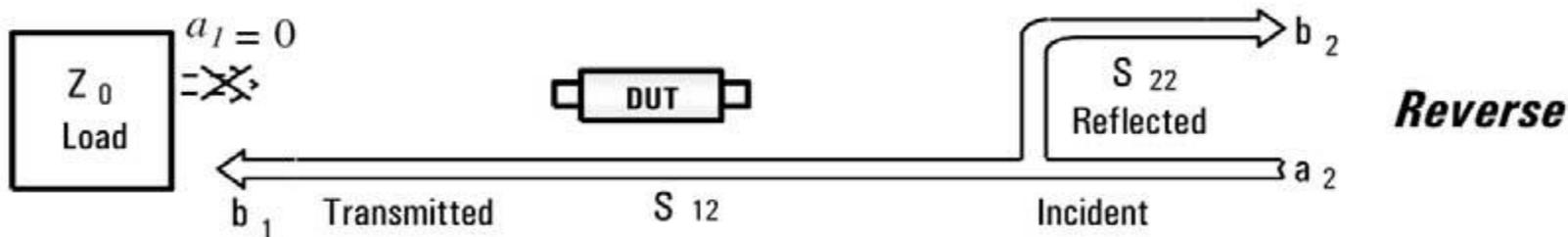


$$S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_1}{a_1} \Big|_{a_2 = 0}$$

$$S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_2}{a_1} \Big|_{a_2 = 0}$$

$$S_{22} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_2}{a_2} \Big|_{a_1 = 0}$$

$$S_{12} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_1}{a_2} \Big|_{a_1 = 0}$$



What do S-parameters Mean ?

S11 = forward reflection coefficient (*input match*)

S22 = reverse reflection coefficient (*output match*)

S21 = forward transmission coefficient (*gain or loss*)

S12 = reverse transmission coefficient (*isolation*)

Remember, S-parameters are inherently complex, linear quantities -- however, we often express them in a log-magnitude format

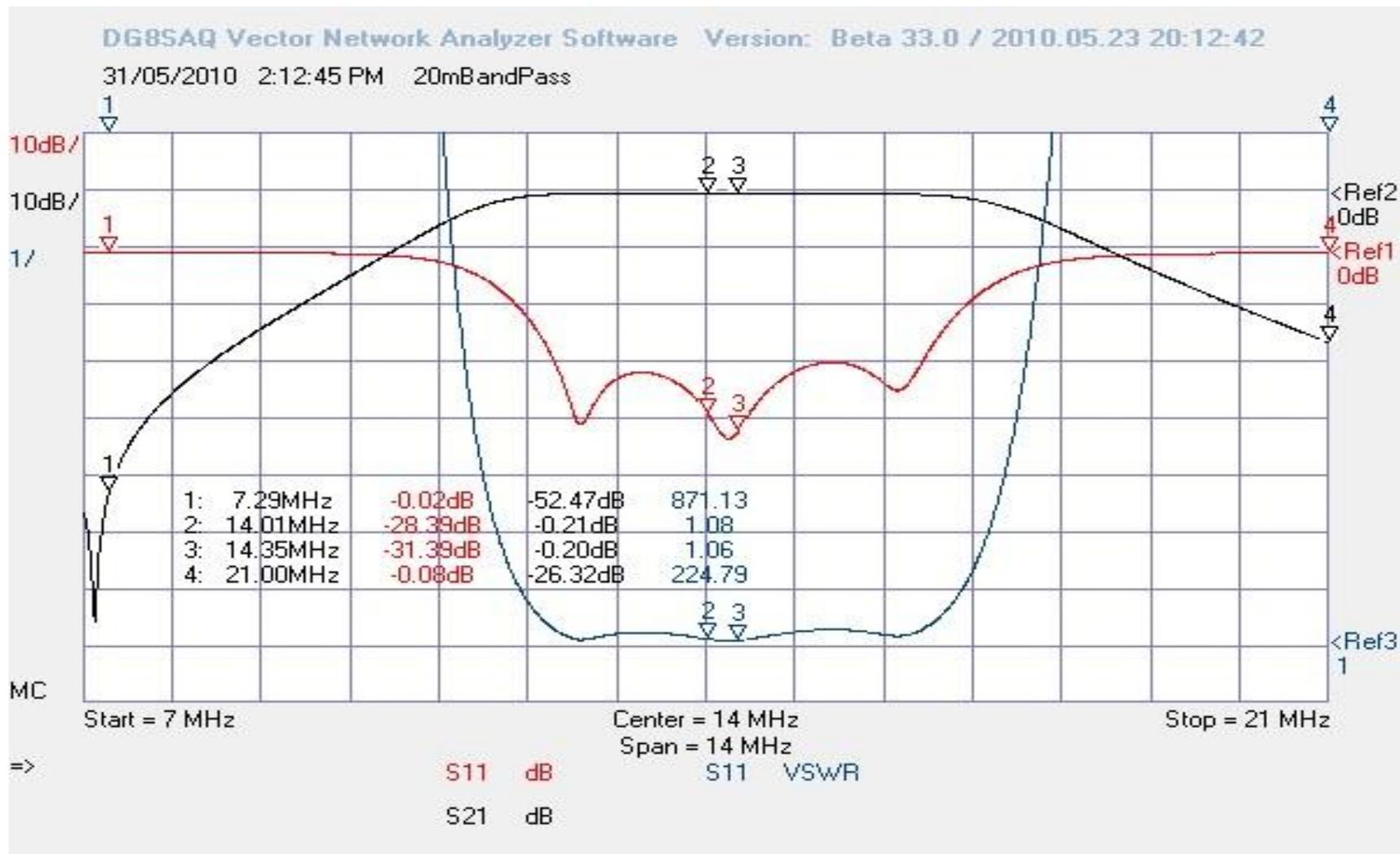
What Does a VNA Do ?

- Sends a controlled voltage signal to the DUT, over a predetermined number of points in a frequency range, and measures, for each point, the reflected voltage and its phase.
- From this , for each freq. point, it calculates:
 - S-parameters, impedance (real, imaginary and absolute) , VSWR, admittance, capacitance, inductance, group delay time and Q.
- Displays a graph of selected parameters vs. frequency and/or in Smith Chart format

Some Applications

- Assess filter characteristics
- Measure antenna VSWR
- Measure inductance
- Measure capacitance
- Determine resonance frequencies
- Measure crystal parameters
- Determine impedance matching circuits
- Measure complex circuit parameters

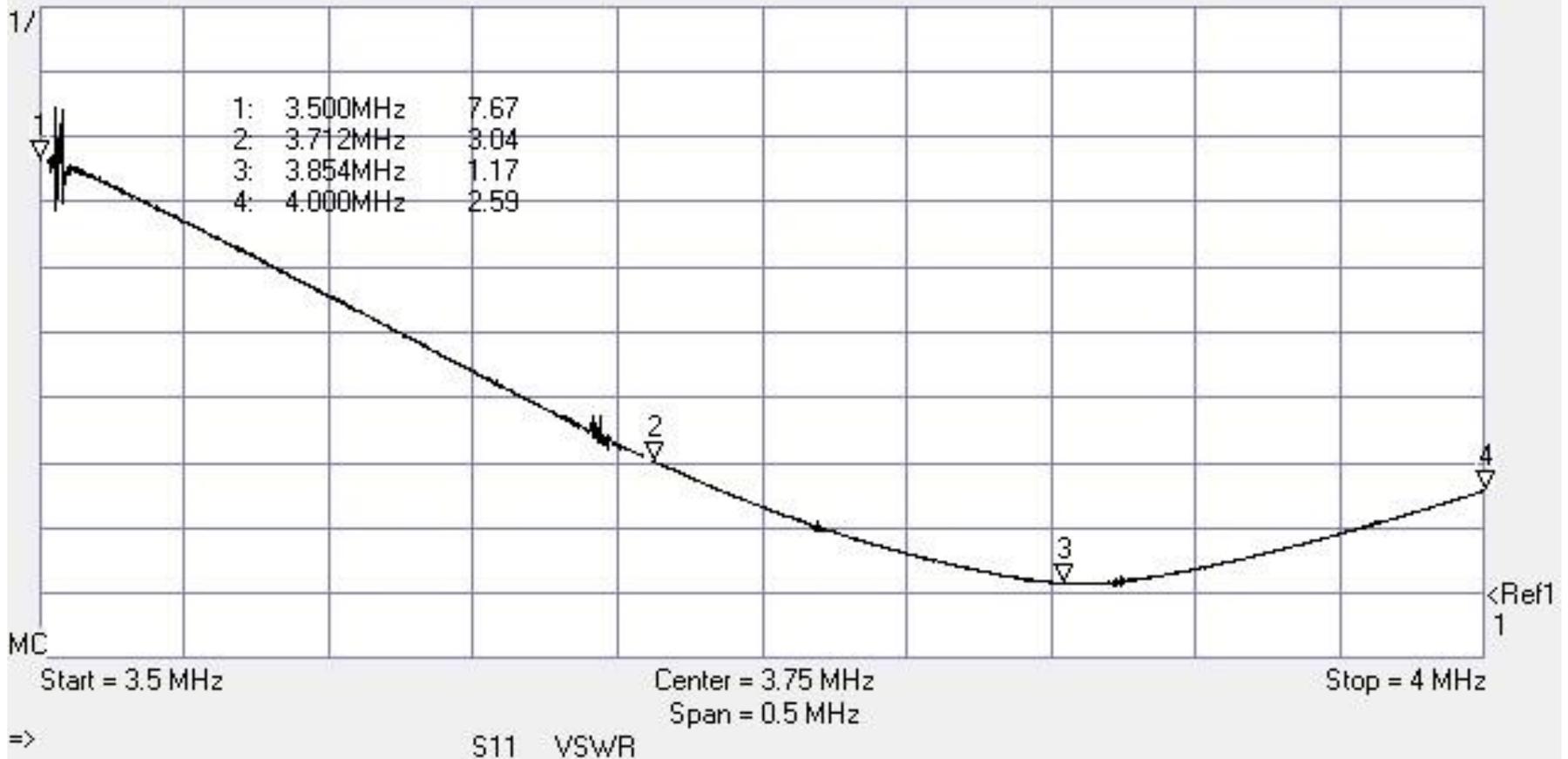
20m Band Pass Filter



VSWR 80m Dipole @ 30 Feet

DG8SAQ Vector Network Analyzer Software Version: Beta 33.0 / 2010.05.23 20:12:42

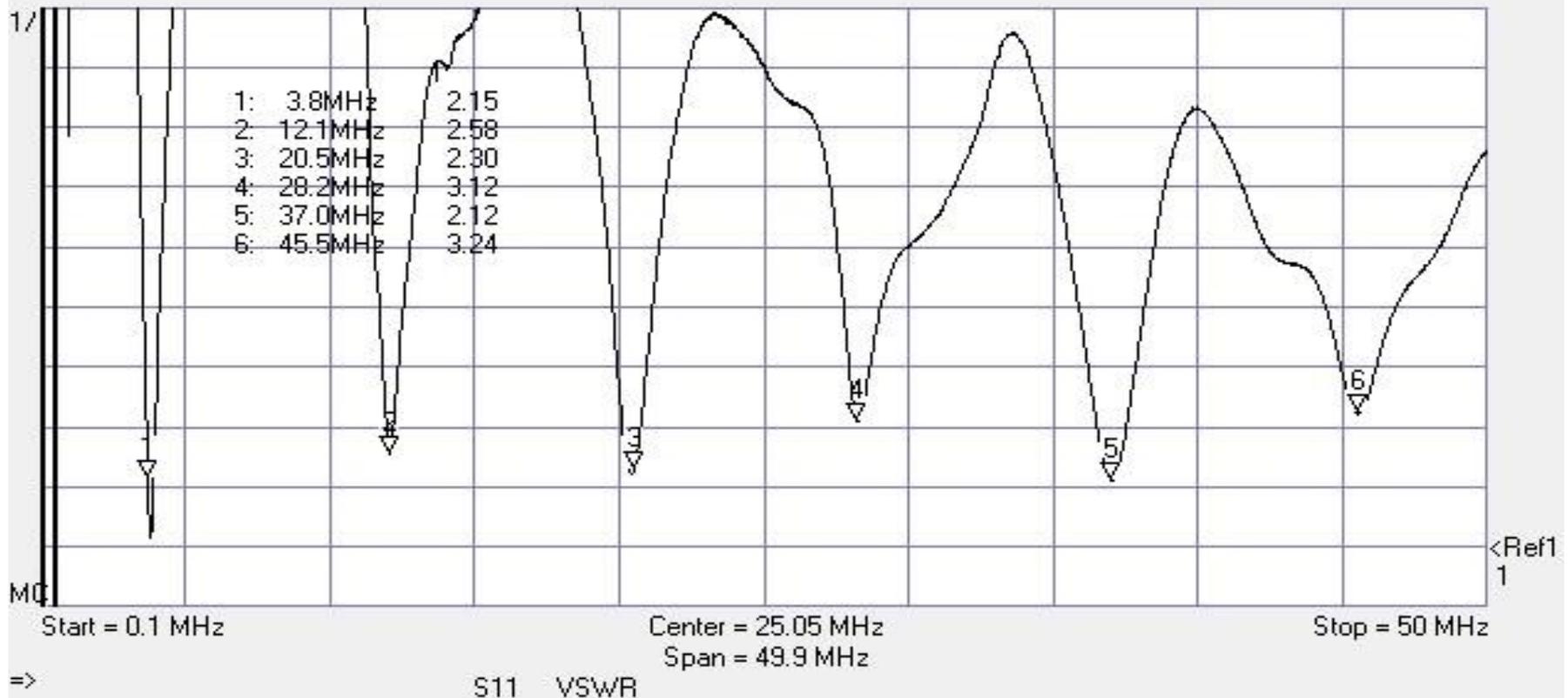
30/05/2010 9:09:49 PM 80mDipole1



VSWR 80m Dipole at 30 feet

DG8SAQ Vector Network Analyzer Software Version: Beta 33.0 / 2010.05.23 20:12:42

30/05/2010 9:05:27 PM 80mDipole2

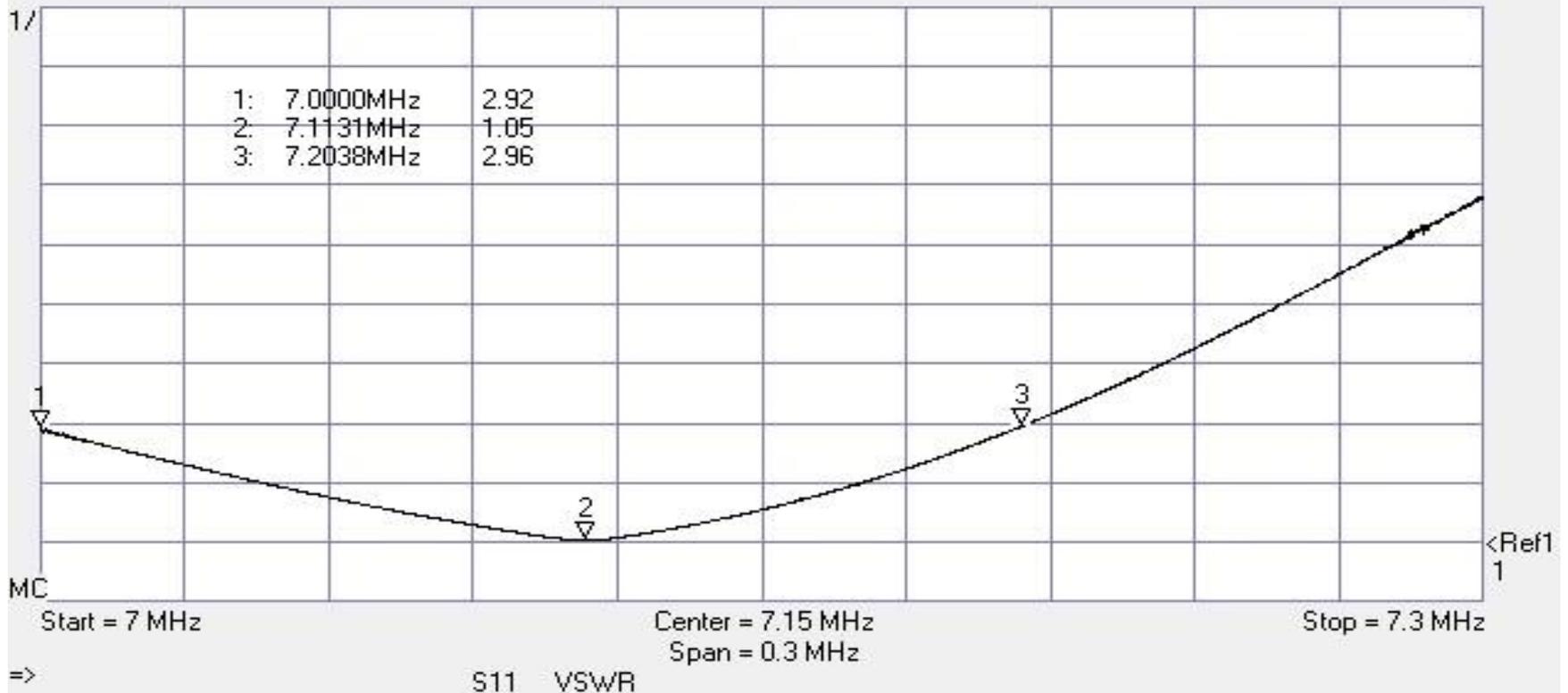


Dipole Resonance

- Note, on the previous slide, that a dipole can resonate at odd multiples of its fundamental frequency (3, 5, 7, 9, 11, etc.)
- The only one of these multiples that's within an amateur band is the seventh, resonant at 28.2 MHz.

VSWR Cushcraft R8 Ant. @ 40m

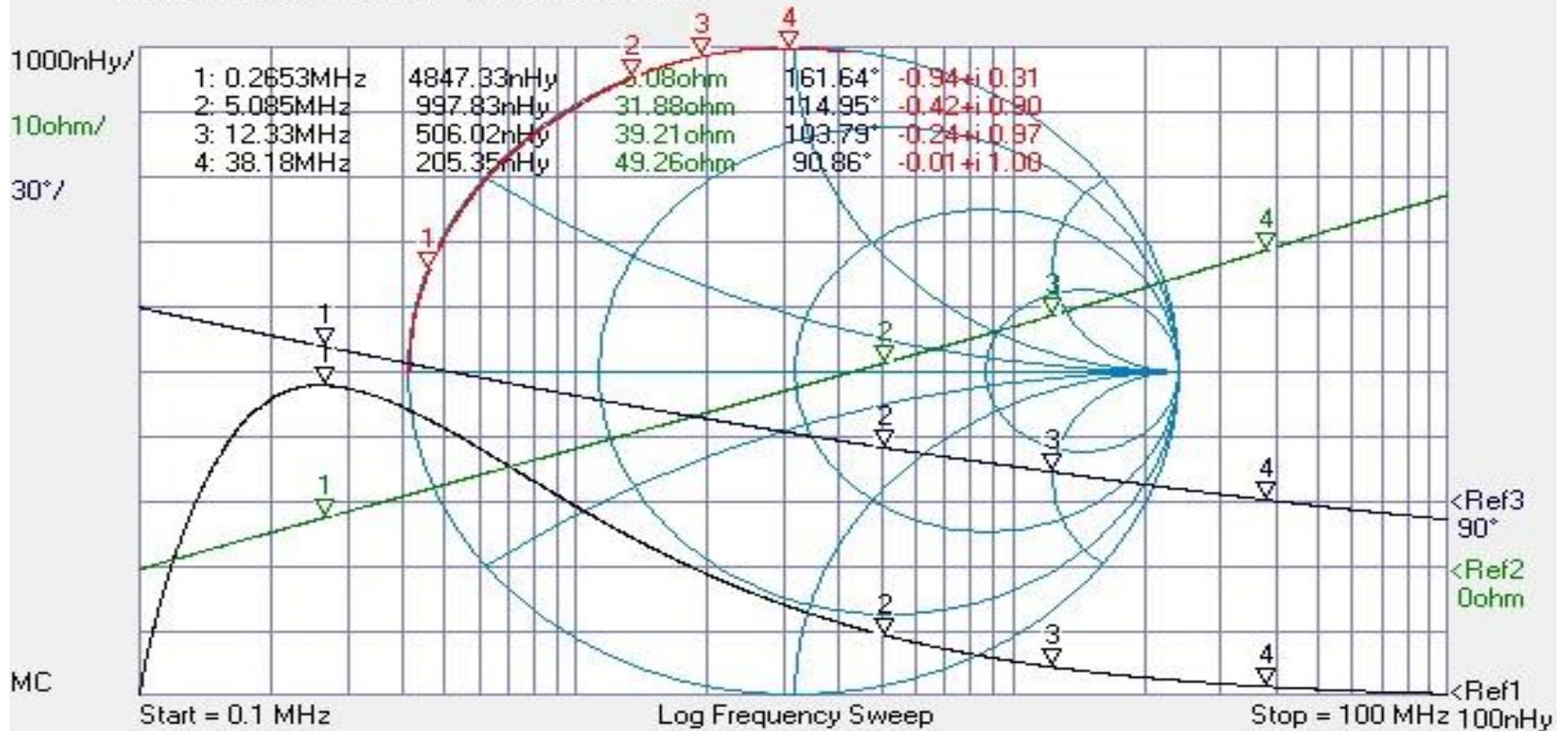
DG8SAQ Vector Network Analyzer Software Version: Beta 33.0 / 2010.05.23 20:12:42
30/05/2010 9:13:25 PM Cushcraft40m



Inductor (205 nH)

DG8SAQ Vector Network Analyzer Software Version: Beta 33.0 / 2010.05.23 20:12:42

30/05/2010 11:56:40 PM Inductance205nH

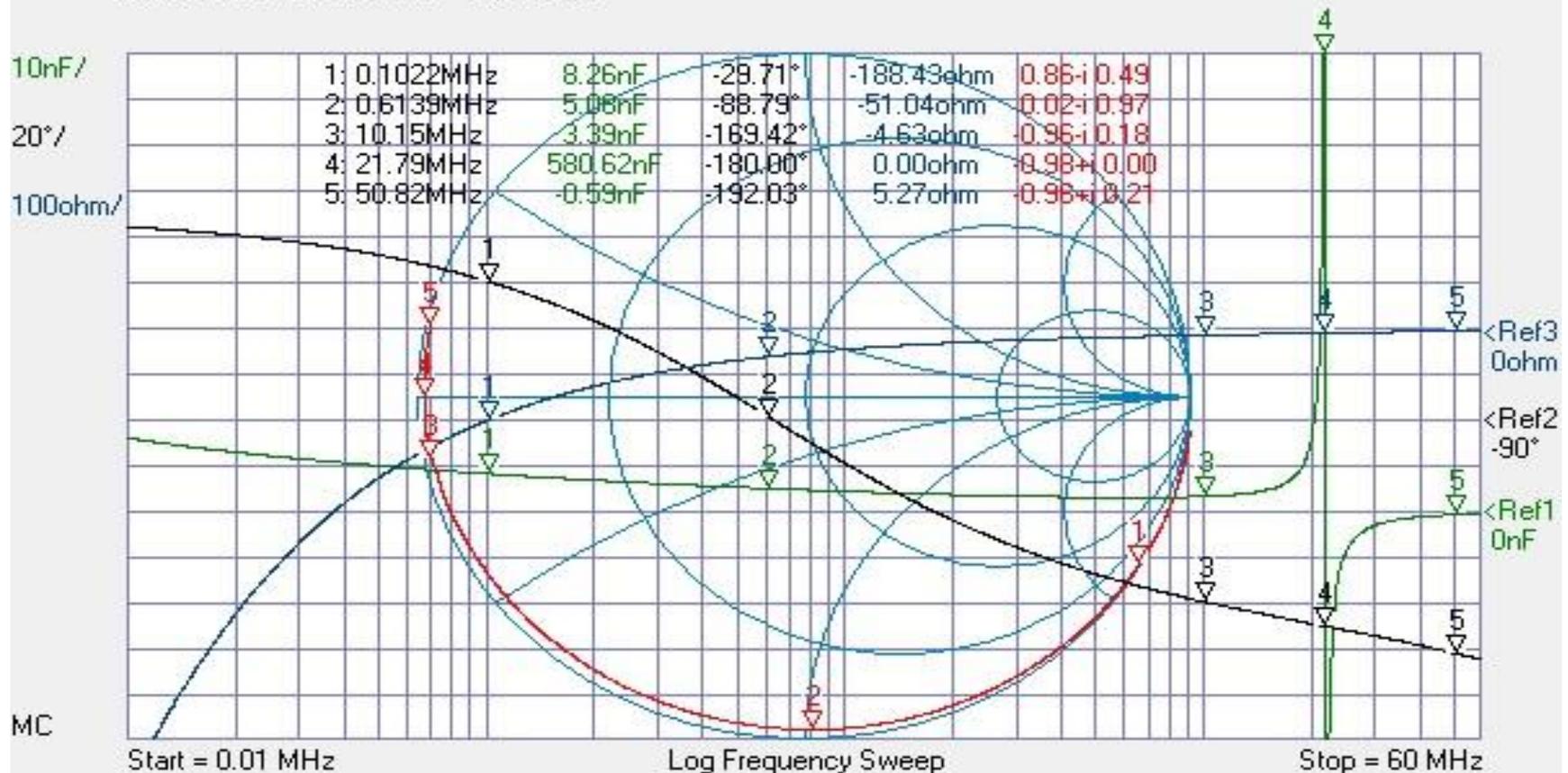


=> S11 L -- S11 c.Phase
 S11 ImagZ S11 Smith

Cap. 1nF -20%/+80%(1.4 nF meas.)

DG85AQ Vector Network Analyzer Software Version: Beta 33.0 / 2010.05.23 20:12:42

31/05/2010 3:06:02 PM Cap1433pF



=>

S11	C--	S11	Imag Z
S11	c.Phase	S11	Smith

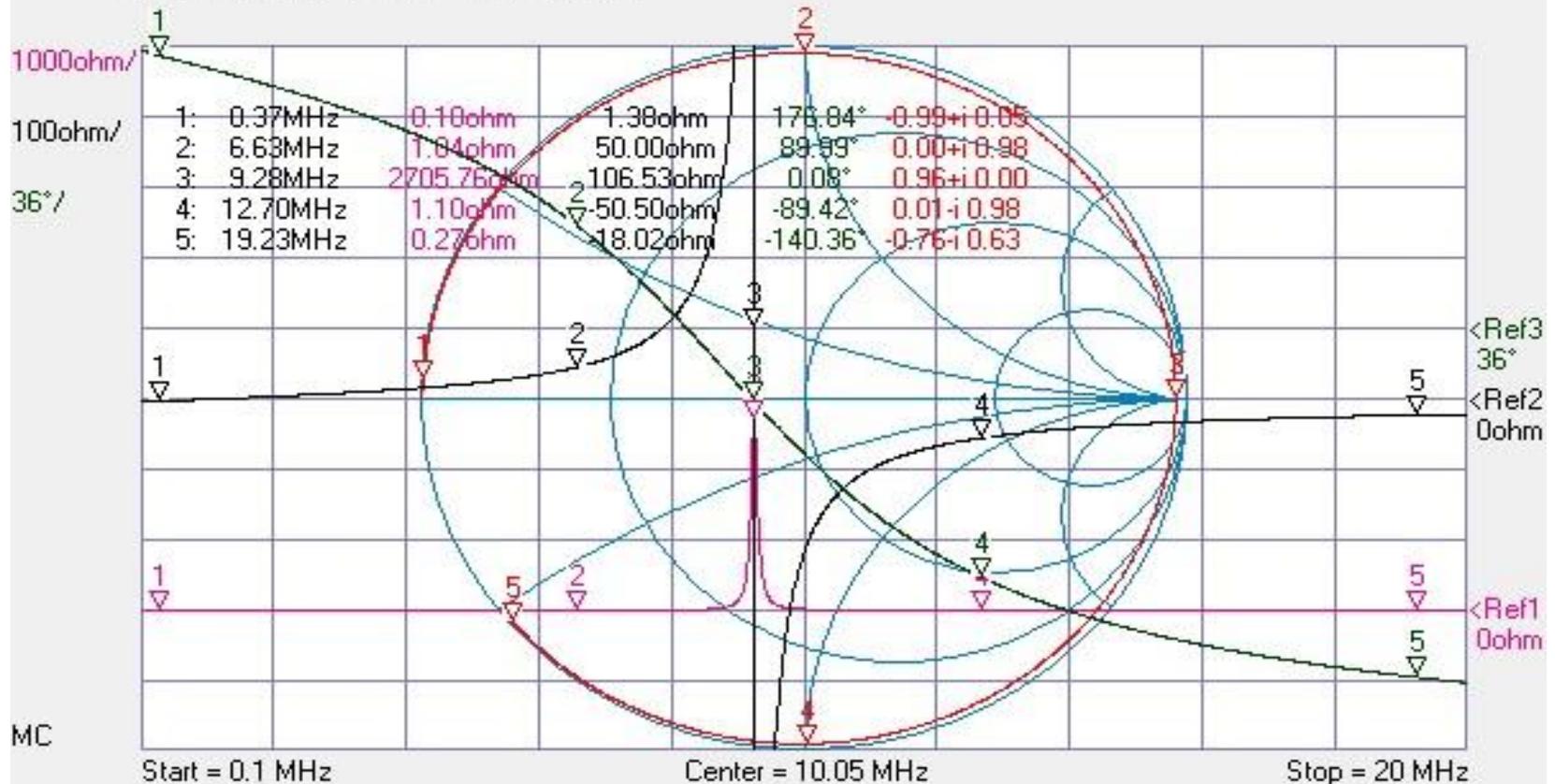
L/C Resonance

- When $(X_L + X_C) = 0$
- Then resonant frequency $f_0 = 1/2\pi \text{ sqrt.}(LC)$
- If measurement of $L = 490 \text{ nH}$ and $C = 461 \text{ pF}$
- Then f_0 is calculated @ 10.6 MHz.
- VNWA shows resonance @ 9.3 MHz.
- Why the difference?

L/C Resonance

DG8SAQ Vector Network Analyzer Software Version: Beta 33.0 / 2010.05.23 20:12:42

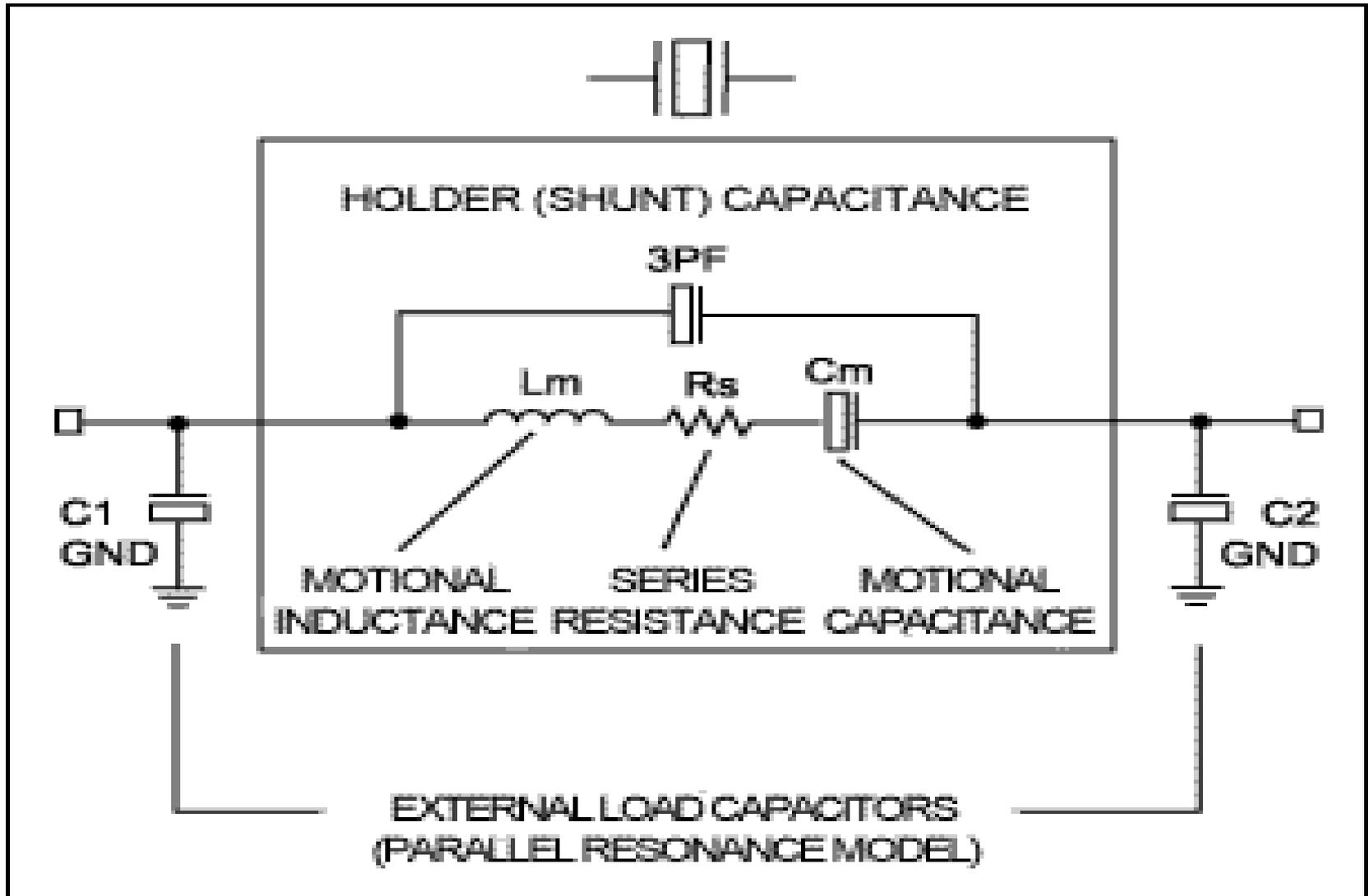
31/05/2010 12:23:56 AM LC/resonance



MC =>

S11 Real Z	S11 c.Phase
S11 Imag Z	S11 Smith

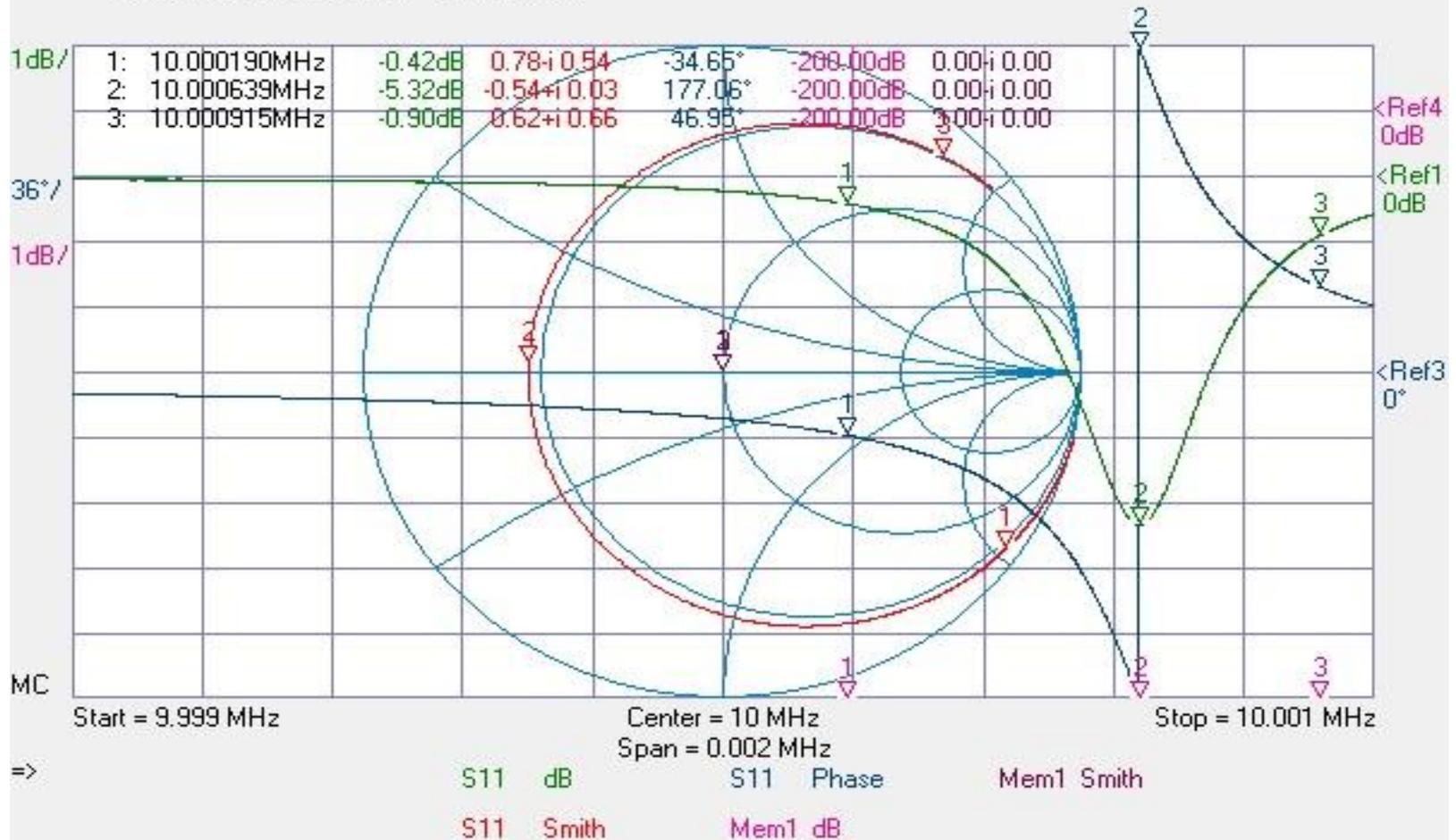
Crystal Parameters



10.0067 MHz. Crystal

DG8SAQ Vector Network Analyzer Software Version: Beta 33.0 / 2010.05.23 20:12:42

04/06/2010 12:39:29 PM 10MHz.Xtal



For Those Who Couldn't Attend

- The VNWA feature was demo'd that calculates the crystal parameters (C_o , L_m , R_s and C_m) that best-fit the graph of the previous slide and that uses these to calculate the resonant frequency of the crystal (10.00063 MHz.)
- This is a quick way to compare many crystals, to select the best ones for filter construction.
- VE3IJS 's low-pass filter was analyzed.