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X-Parameters: The Power to Create a Paradigm Shift in Nonlinear Design?

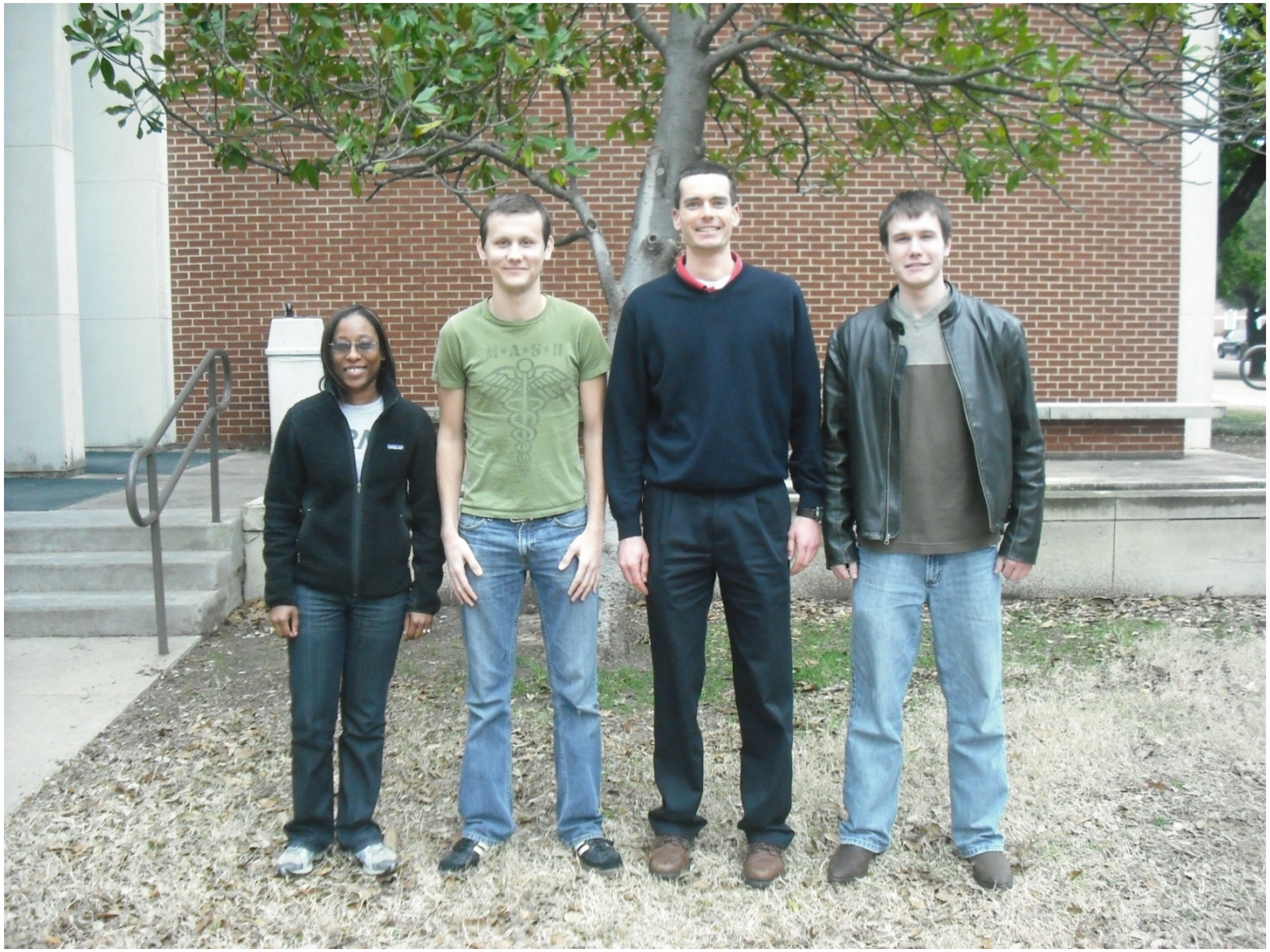
Dr. Charles Baylis

Baylor Engineering and Research Seminar (B.E.A.R.S.)
February 24, 2010

Acknowledgments

- Dr. Robert J. Marks II – faculty collaborator
- Josh Martin, Joseph Perry, Matthew Moldovan, Hunter Miller – student collaborators
- X-Parameters is a registered trademark of Agilent Technologies.

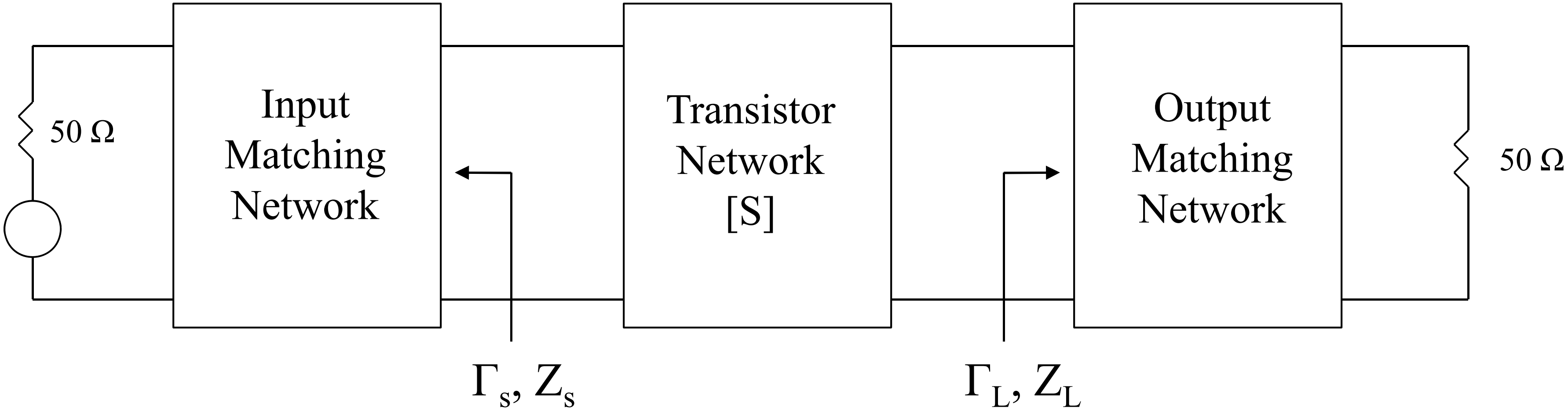
WMCS Active Circuit Research Group



Agenda

- The Microwave Amplifier Design Problem
- Linear Network Parameters
- X-Parameters for Nonlinear Devices
- Research Goals
- Conclusions

The Microwave Amplifier Design Problem*



- Small-signal design is based solely on the S-parameters of the transistor network.
- Γ_s(or Z_s) and Γ_s, Z_s are chosen for design criteria including gain, efficiency, linearity, stability, and noise figure.

*G. Gonzalez, *Microwave Transistor Amplifiers: Analysis and Design*, Second Edition, Prentice-Hall, 1997.

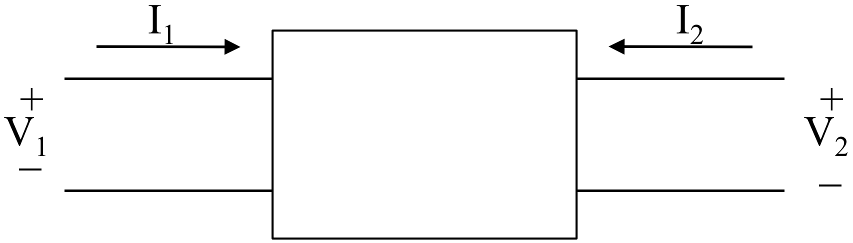
Small-Signal vs. Large-Signal

- Small-Signal
  - We "bias" the device and then superimpose a <u>very small</u> (→0) AC waveform.
  - Designs can be based on S-parameters of the active device.
- Large-Signal
  - The AC signal on top of the DC bias <u>cannot</u> be considered of negligible amplitude.
  - Nonlinear models or measurements must be used to design.

Small-Signal Design

- Can be accomplished using linear network parameters.
- The measurement is all you need!
- Can calculate gain, noise figure, and stability as a function of
  - Device S-parameters
  - Source and load terminating impedances

Small-Signal Z-Parameters



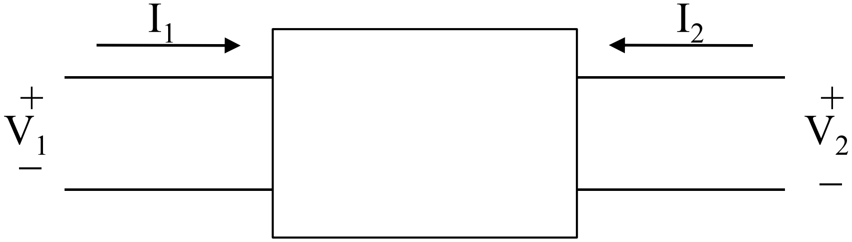
$$V_1 = Z_{11} I_1 + Z_{12} I_2$$

$$V_2 = Z_{21} I_1 + Z_{22} I_2$$

$$Z_{11} = \left.\frac{V_1}{I_1}\right|_{I_2=0} \qquad Z_{21} = \left.\frac{V_2}{I_1}\right|_{I_2=0} \qquad Z_{12} = \left.\frac{V_1}{I_2}\right|_{I_1=0} \qquad Z_{22} = \left.\frac{V_2}{I_2}\right|_{I_1=0}$$

- Open-circuit appropriate port.
- Apply current.
- Measure voltage.

Small-Signal Y-Parameters



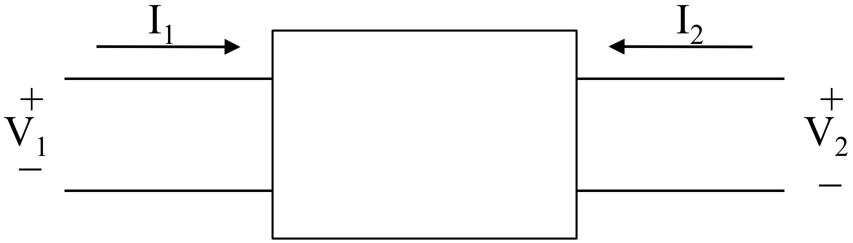
$$I_1 = Y_{11}V_1 + Y_{12}V_2$$

$$I_2 = Y_{21}V_1 + Y_{22}V_2$$

$$Y_{11} = \left.\frac{I_1}{V_1}\right|_{V_2=0} \qquad Y_{21} = \left.\frac{I_2}{V_1}\right|_{V_2=0} \qquad Y_{12} = \left.\frac{I_1}{V_2}\right|_{V_1=0} \qquad Y_{22} = \left.\frac{I_2}{V_2}\right|_{V_1=0}$$

- Short-circuit appropriate port.
- Apply voltage.
- Measure current.

Small-Signal Y-Parameters



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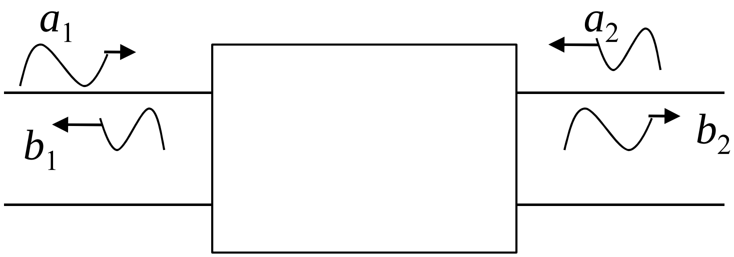
- Short-circuit appropriate port.
- Apply voltage.
- Measure current.

Small-Signal S-Parameters

- Traveling voltage waves are easier to measure at microwave frequencies than total voltage and current.
- Divide V_1 into two components:
  - a_1 = voltage wave entering the network
  - b_1 = voltage wave leaving the network
- Divide V_2 into two components:
  - a_2 = voltage wave entering the network
  - b_2 = voltage wave leaving the network

Small-Signal S-Parameters



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

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

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0} \qquad S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0} \qquad S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0} \qquad S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$$

- Make sure no reflections occur from appropriate port (terminate it in Z_0).
- Apply incident wave to the other port.
- Measure wave leaving appropriate port.

Small-Signal S-Parameters

- Can be easily measured with a vector network analyzer (VNA):

- Can be calculated from Y or Z parameters (and vice versa).

Small-Signal Amplifier Design Gain Equations

- Based only on S-parameters and source/load terminating impedances:

$$G_p = \frac{1}{1 - \Gamma_{IN}} \left|S_{21}\right|^2 \frac{1 - \left|\Gamma_L\right|^2}{\left|1 - S_{22}\Gamma_L\right|^2}$$

where

$$\Gamma_{IN} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L}$$

Small-Signal Amplifier Optimum Load and Source Impedances

- Can be calculated directly from S-parameters:

$$\Gamma_{Ms} = \frac{B_1 \pm \sqrt{B_1^{\,2} - 4\left|C_1\right|^2}}{2C_1} \qquad \Gamma_{ML} = \frac{B_2 \pm \sqrt{B_2^{\,2} - 4\left|C_2\right|^2}}{2C_2}$$

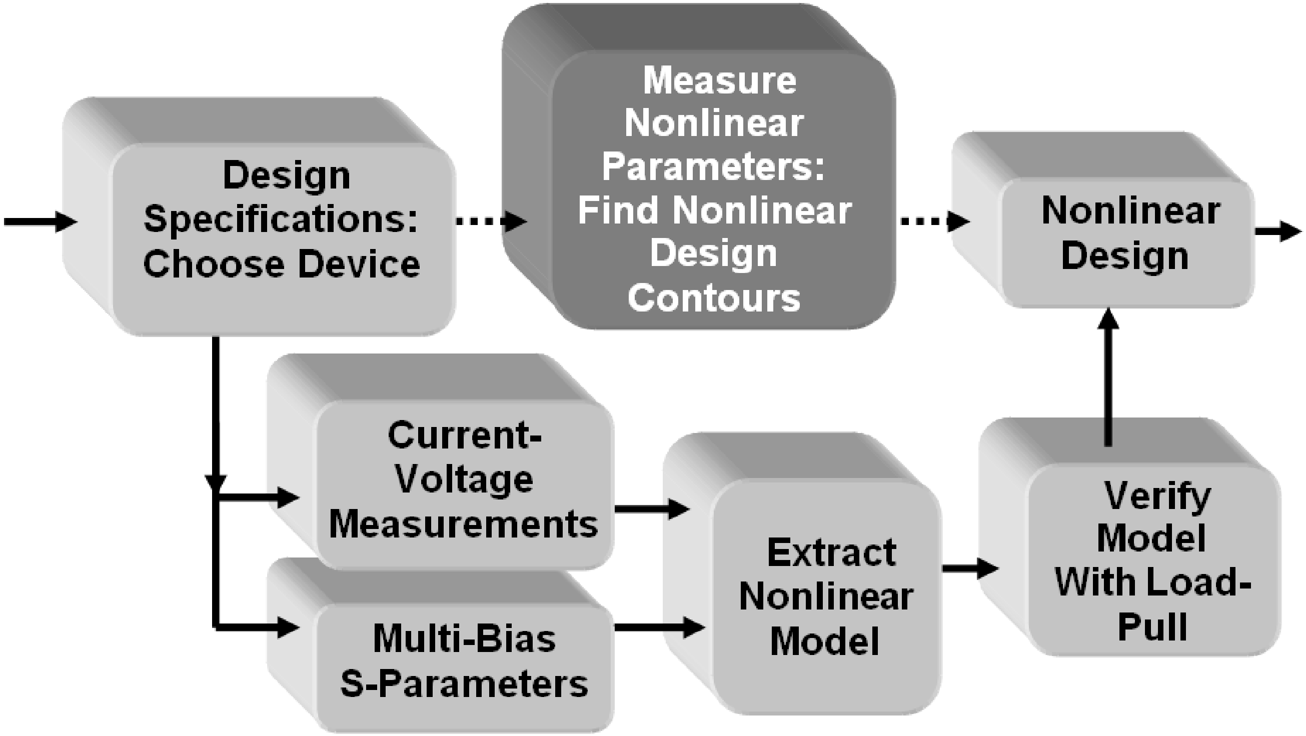
(B_1, B_2, C_1, C_2 are functions of [S].)

- Contours of equal gain (less than maximum), noise, and stability circles can be plotted on the complex Γ_L and/or Γ_s planes (Smith Charts)

Large-Signal Amplifier Design

- Without nonlinear network parameters, requires bench-top load pull or an accurate nonlinear transistor model.
- Nonlinear transistor model extraction requires
  - Current-voltage measurement(s)
  - S-Parameters at multiple transistor bias points.
  - A skilled engineer to do the extraction (20 to 50 parameters!)
  - Load-pull measurements for validation
- Is there a method analogous to the small-signal S-parameters using X-parameters that can predict large-signal gain?
- TOI? ACPR?, etc.

Revolutionizing the Nonlinear Design Cycle: Nonlinear Network Parameters

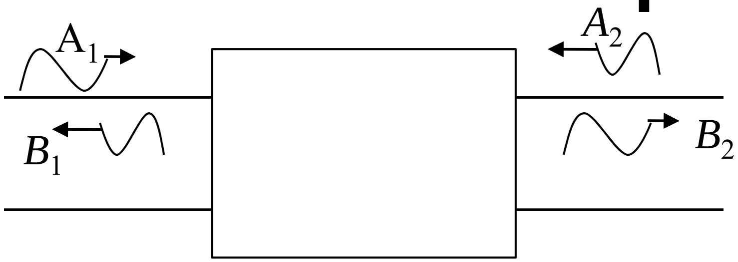


Agilent X-Parameters*

- Allow network characterization in a method similar to small-signal.
- Measurements required:
  - Signal Magnitude (Input and Output)
  - Signal Phase (Input and Output)
- Calibrations required:
  - Magnitude at fundamental and all harmonics
  - Phase at fundamental (can skip harmonics?)

*X-parameters is a registered trademark of Agilent Technologies.

X-Parameter Equation*



$$B_{ef} = X^{(F)}_{ef}\left(\left|A_{11}\right|\right)P^{f} + \sum_{g,h} X^{(S)}_{ef,gh}\left(\left|A_{11}\right|\right)P^{f-h}a_{gh} + \sum_{g,h} X^{(T)}_{ef,gh}\left(\left|A_{11}\right|\right)P^{f+h}a^{*}_{gh}$$

Each X parameter is a function of $|A_{11}|$.

$P = e^{j\angle A_{11}}$ provides phase correction for harmonic conversion.

$$X^{(S)}_{ef,gh}$$

Arrival Port

Arrival Harmonic

Departure Port

Departure Harmonic

*D. Root, “A New Paradigm for Measurement, Modeling, and Simulation of Nonlinear Microwave and RF Components,” Presentation at Berkeley Wireless Research Center, April 2009.

X-Parameter Equation

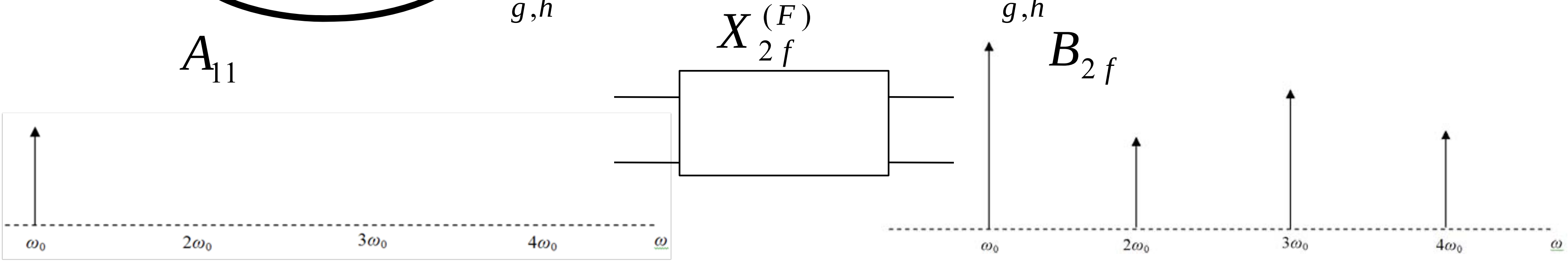
$$B_{ef} = X_{ef}^{(F)}\left(\left|A_{11}\right|\right)P^{f} + \sum_{g,h} X_{ef,gh}^{(S)}\left(\left|A_{11}\right|\right)P^{f-h}a_{gh} + \sum_{g,h} X_{ef,gh}^{(T)}\left(\left|A_{11}\right|\right)P^{f+h}a_{gh}^{*}$$

- First Term: Output at port *e* and harmonic *f* due to large-signal input at port 1 and fundamental.
- Second and Third Terms: Output at port *e* and harmonic *f* due to small-signal perturbations perturbations at all ports and harmonics.

Measuring 2-Port X-Parameters

$$X_{ef}^{(F)}$$

$$B_{ef} = \boxed{X_{ef}^{(F)}\left(\left|A_{11}\right|\right)P^{f}} + \sum_{g,h} X_{ef,gh}^{(S)}\left(\left|A_{11}\right|\right)P^{f-h}a_{gh} + \sum_{g,h} X_{ef,gh}^{(T)}\left(\left|A_{11}\right|\right)P^{f+h}a_{gh}^{*}$$



- Negative-frequency side of Fourier spectrum is identical.
- a_{gh}, a_{gh}^{*} (small signals) set to zero.
- Measure magnitude and phase of output harmonics at ports 1 and 2 .

$$X_{ef}^{(F)}\left(\left|A_{11}\right|\right) = \frac{B_{ef}}{P^{f}}$$

Measuring 2-Port X-Parameters

$$B_{ef} = X^{(F)}_{ef}\left(|A_{11}|\right)P^{f} + \sum_{g,h} X^{(S)}_{ef,gh}\left(|A_{11}|\right)P^{f-h}a_{gh} + \sum_{g,h} X^{(T)}_{ef,gh}\left(|A_{11}|\right)P^{f+h}a^{*}_{gh}$$

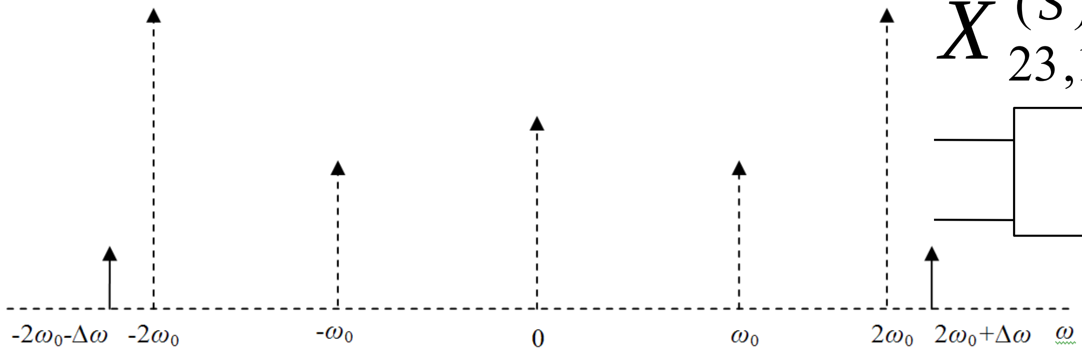


Figure 4. Frequency Content of the Input Cosine Signal $a_{12} + a_{12}^*$

$$X^{(S)}_{23,12} \qquad X^{(T)}_{23,12}$$

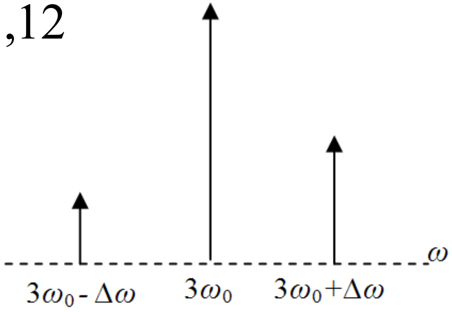


Figure 2. Frequency Content of the Output Component B_{23}

$$a_{gh} + a^{*}_{gh} = 2\,\mathrm{Re}(a_{gh})$$

- A cosine input has positive and negative frequency content.
- Mixing is caused by the nonlinearities, causing two sums to arise at each frequency; one from the negative frequency and one from the positive frequency.

Measuring 2-Port X-Parameters

$$B_{ef} = X^{(F)}_{ef}\left(|A_{11}|\right)P^{f} + \sum_{g,h} X^{(S)}_{ef,gh}\left(|A_{11}|\right)P^{f-h} a_{gh} + \sum_{g,h} X^{(T)}_{ef,gh}\left(|A_{11}|\right)P^{f+h} a^{*}_{gh}$$

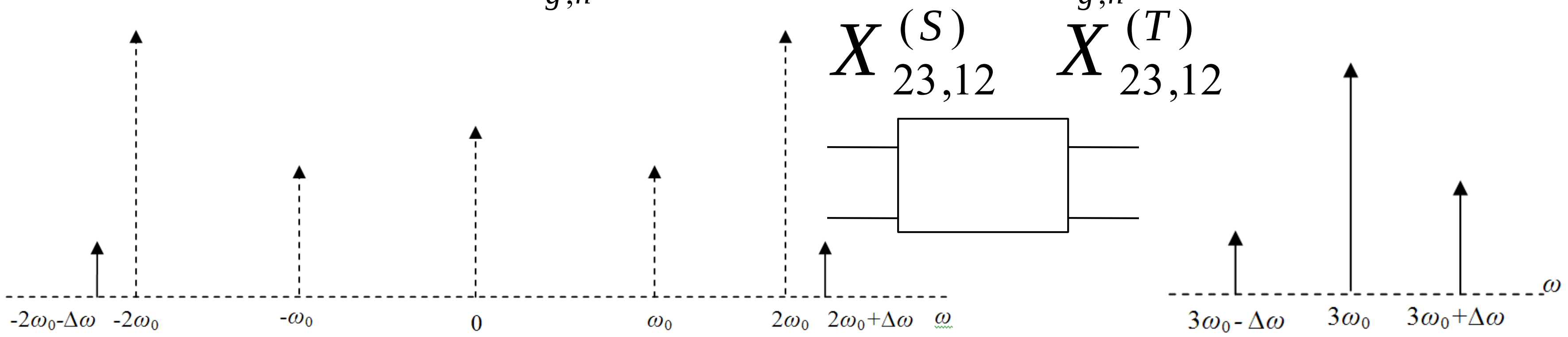


Figure 4. **Frequency Content of the Input Cosine Signal $a_{12} + a_{12}^{*}$**

Figure 2. Frequency Content of the Output Component B_{23}

$$a_{gh} + a^{*}_{gh} = 2\,\mathrm{Re}(a_{gh})$$

- In this case, conversion by addition to $3\omega_0$ from $2\omega_0$ can be accomplished by adding ω_0 and from $-2\omega_0$ by adding $5\omega_0$.
- The *P* exponential is the number of harmonics added to perform each conversion.
- Terms from a_{gh} is above the destination frequency and the term from a_{gh}^{*} is slightly below the destination frequency.

Measuring 2-Port X-Parameters

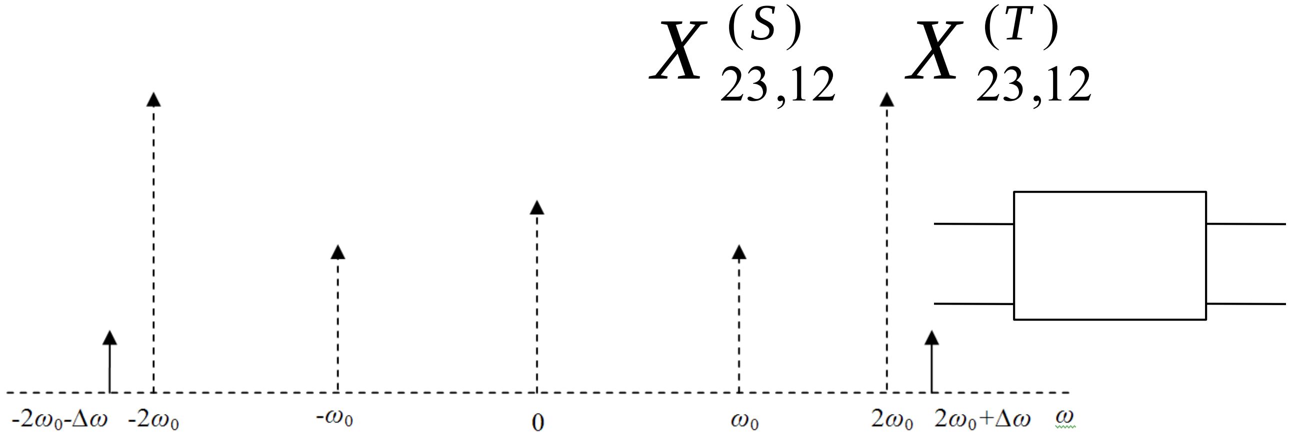


Figure 4. **Frequency Content of the Input Cosine Signal $a_{12} + a_{12}{}^*$**

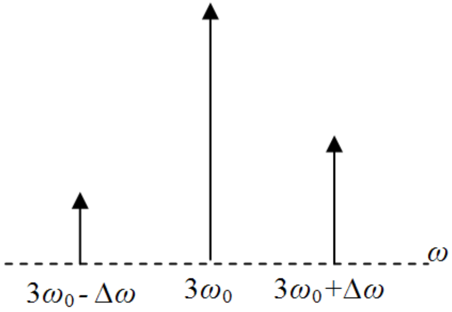


Figure 2. Frequency Content of the Output Component B_{23}

High Term, Cosine Measurement: $$X^{(S)}_{ef,gh} = \frac{|B_{ef}(\text{cosine}, high)|\, e^{j\theta}}{P^{f-h} a_{gh}}$$

Low Term, Cosine Measurement: $$X^{(T)}_{ef,gh} = \frac{|B_{ef}(\text{cosine}, low)|\, e^{j\phi}}{P^{f+h} a^*_{gh}}$$

High Term, Sine Measurement: $$X^{(S)}_{ef,gh} = \frac{|B_{ef}(\text{sine}, high)|\, e^{j\left(\theta-\frac{\pi}{2}\right)}}{P^{f-h} a_{gh}}$$

High Term, Sine Measurement: $$X^{(T)}_{ef,gh} = \frac{|B_{ef}(\text{sine}, low)|\, e^{j\left(\phi+\frac{\pi}{2}\right)}}{P^{f+h} a^*_{gh}}$$

→4 equations, 4 unknowns. If phase measurements can be performed, then only two measurements are required.

X-Parameters Research Topics

- Nonlinear Amplifier Design Theory Paralleling the Linear Design Approach
- Measurement
- Using X-Parameters in Other Disciplines

Nonlinear Amplifier Design with X-Parameters

- Derive equations similar to the small-signal equations such as

$$G_p = \frac{1}{1-\Gamma_{IN}}\left|S_{21}\right|^2 \frac{1-\left|\Gamma_L\right|^2}{\left|1-S_{22}\Gamma_L\right|^2}$$

$$\Gamma_{Ms} = \frac{B_1 \pm \sqrt{B_1{}^2 - 4\left|C_1\right|^2}}{2C_1} \qquad \Gamma_{ML} = \frac{B_2 \pm \sqrt{B_2{}^2 - 4\left|C_2\right|^2}}{2C_2}$$

- Calculate and plot gain, stability, third-order intercept (TOI), noise contours on the Smith chart.
- Assess necessary compromises and complete design.
- This may eliminate the arduous “middle-man” of nonlinear transistor modeling. The results also will be based directly on measurement data and will be more accurate!

Measurements

- Typical measurements must be made with a nonlinear vector network analyzer (NVNA) such as the Agilent PNA-X (very expensive).
- Can we measure without a NVNA?
- Vector Signal Analyzer(s), Vector Signal Generator(s) needed for testing of these techniques.
- Could create software routines to automate magnitude and phase calibration at fundamental and considered harmonics.
- To allow a paradigm shift, measurements must be accessible.

Using X-Parameters in Other Disciplines

- Power Electronics
  - Total Harmonic Distortion
  - Characterizing unwanted nonlinearities.
- “Smart” Systems for Clean Power Signals
  - Measure X-parameters of a system.
  - Apply appropriate signal predistortion or system correction to result in a clean signal.
- Vibrations
  - Assess nonlinearities of a vibrational system.
  - Could this be applied to design?

Conclusions

- Nonlinear network functions may be able to revolutionize how nonlinear circuits (and possibly other types of systems) are designed.
- Circuits may be designed directly from nonlinear measurement data; designs will rely less on nonlinear models.
- Associated measurement techniques may save companies money, allowing the paradigm shift to occur.
- Nonlinear network parameters seem to show promise of being useful in other interdisciplinary areas.

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