BAYLOR
UNIVERSITY

WIRELESS AND MICROWAVE
CIRCUITS AND SYSTEMS

Solid State Amplifiers for Next-Generation Radar Transmitters

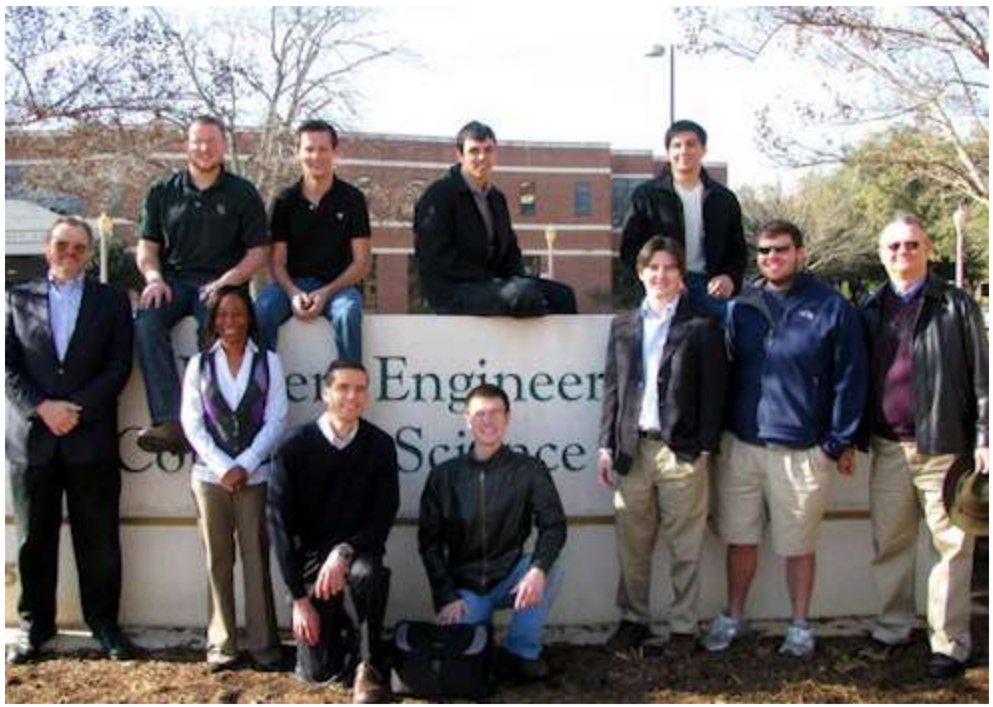
Dr. Charles Baylis
2011 International Symposium on Advanced Radar Technologies (ISART 2011)
Boulder, Colorado
July 2011

Outline

- Baylor WMCS Program and Activities
- Review of Single-Stage Amplifier Classes
- Advanced Power Amplifier Architectures
- Real-Time Load-Impedance Optimization
- The Way Forward
  - Joint Waveform and Circuit Optimization
  - Wirtinger Calculus for TIPP Systems

Baylor WMCS Program

- Wireless and Microwave Circuits and Systems
- Wireless and Microwave Education and Research in a Caring, Christian Environment
- Launched in 2008.



Research

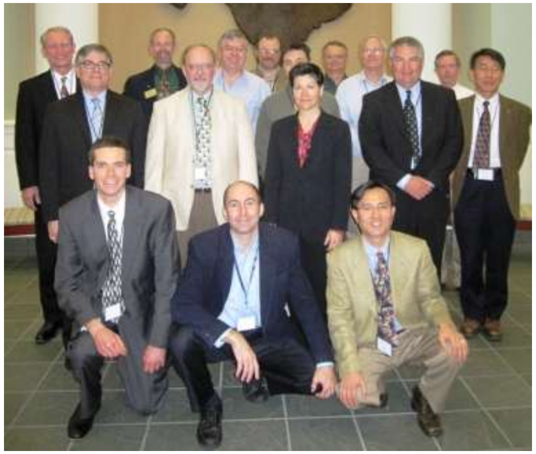
- Faculty
  - Dr. Charles Baylis, Co-Director, microwave power amplifier design, waveform diversity
  - Dr. Randall Jean, Co-Director, microwave sensors and metrology
  - Dr. Yang Li – antenna design
  - Dr. Robert J. Marks II – computational intelligence
  - Dr. Steve Eisenbarth – wireless networks
  - Dr. Mike Thompson - communications
- Graduate and undergraduate student research and teaching assistants

WMCS Teaching Laboratory

- Founded in 2009 with partial sponsorship from Agilent Technologies.
- "Hub" for hands-on teaching activity.
- Provides hands-on component for RF/Microwave Circuits course sequence.

WMCS Advisory Board and Mini-Symposium

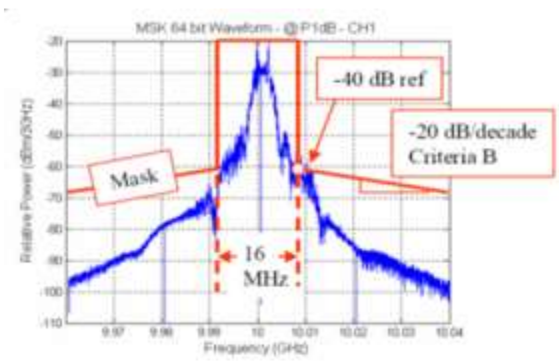
- Industry Advisory Board created in 2009 to assist with educational and research mission.
- Annual Mini-Symposium on Wireless and Microwave Circuits and Systems
  - Student/industry forum
  - 5 universities participated in 2011.



Transmitter Amplifier Constraints

- Amplifiers must transmit large amounts of power with high power efficiency.
- Radar spectrum criteria imposed in the Radar Spectrum Evaluation Criteria (RSEC), which are determined by the National Telecommunications and Information Administration (NTIA).
- Spectral mask outlines the required confines of the signal:

*Reprinted from J. de Graaf, H. Faust, J. Alatishe, and S. Talapatra, “Generation of Spectrally Confined Transmitted Radar Waveforms,” Proc. IEEE Conf. on Radar, 2006, pp. 76-83



Sources of Nonlinearity

- A major source of spectral spreading is third-order intermodulation distortion in the amplifier transistor.
- Assume a third-order nonlinear system approximated by

$$v_{out}(t) = a + bv_{in}(t) + cv_{in}{}^{2}(t) + dv_{in}{}^{3}(t)$$

- Stimulate with a two-tone input signal:

$$v_{in}(t) = A\cos\omega_1 t + B\cos\omega_2 t$$

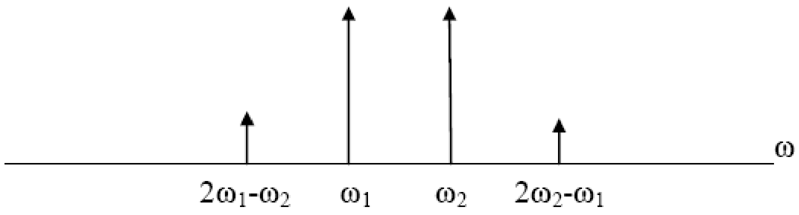
Math Results

$$v_{out}(t) = a + b(A\cos\omega_1 t + B\cos\omega_2 t) + c(A\cos\omega_1 t + B\cos\omega_2 t)^2 + d(A\cos\omega_1 t + B\cos\omega_2 t)^3$$

$$v_{out}(t) = a + b(A\cos\omega_1 t + B\cos\omega_2 t) + c(A^2\cos^2\omega_1 t + B^2\cos^2\omega_2 t + 2AB\cos\omega_1 t\cos\omega_2 t)^2 + d(A^2\cos^2\omega_1 t + B^2\cos^2\omega_2 t)(A\cos\omega_1 t + B\cos\omega_2 t)$$

$$v_{out}(t) = a + b(A\cos\omega_1 t + B\cos\omega_2 t) + c(A^2\cos^2\omega_1 t + B^2\cos^2\omega_2 t + 2AB\cos\omega_1 t\cos\omega_2 t)^2 + d(A^3\cos^3\omega_1 t + A^2B\cos^2\omega_1 t\cos\omega_2 t + AB^2\cos\omega_1 t\cos^2\omega_2 t + B^3\cos^3\omega_2 t)$$

Third-Order Intermodulation Terms



Intermodulation Results

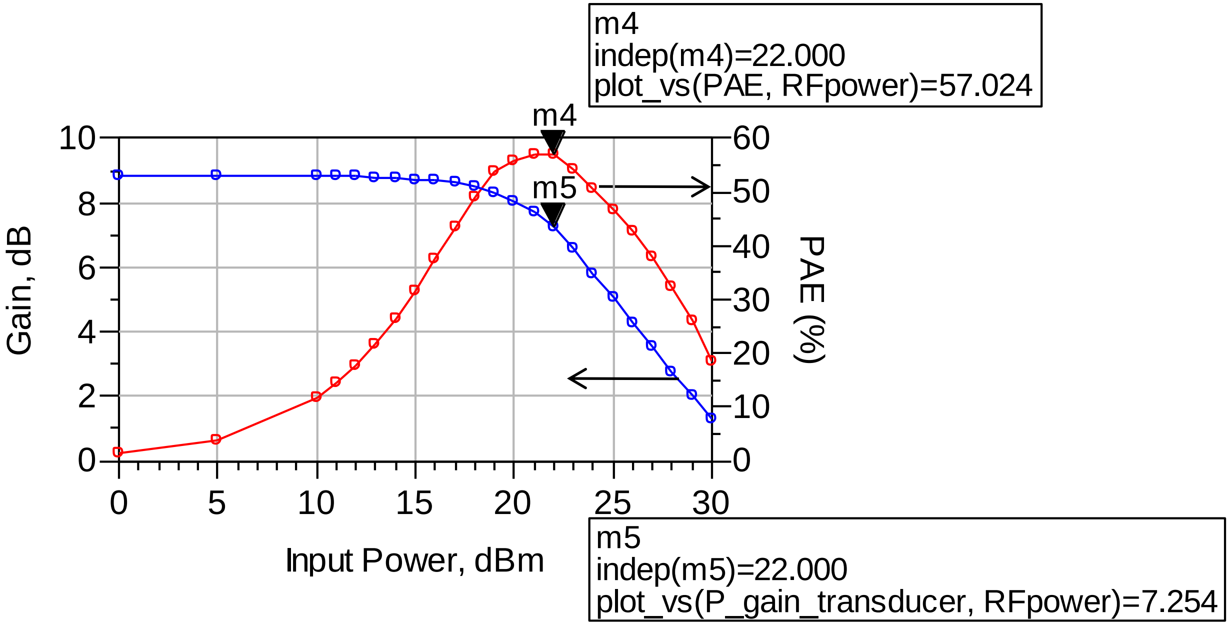
- For a bandpass signal, each frequency at which the signal is nonzero represents a "tone".
- In general, all pairs of tones intermodulate:
  - In-band distortion
  - Out-of-band distortion ("spectral spreading")

How to Remove the Sidelobes?

- Filtering?
  - Radar systems often operate in megawatt range.
  - It is difficult to use microstrip cavity filter capabilities over 1 kW.
  - Not cost-effective or practical
- Linearization
  - Remove the sidelobes by making the amplifier more linear.
  - We need to maintain efficiency at the same time.

Linearity vs. Efficiency

- Efficiency increases with output power.
  - GaAs MESFET power amplifier example shown below.
- Linearity decreases with increasing output power for amplitude modulated signals.



Efficiency Measures

- Drain Efficiency:

$$\eta = \frac{P_{out,RF}}{P_{DC}}$$

- Power-Added Efficiency:

$$\eta_{ADD} = \frac{P_{out,RF} - P_{in,RF}}{P_{DC}}$$

- Overall Efficiency:

$$\eta_{OVERALL} = \frac{P_{out,RF}}{P_{DC} + P_{in,RF}}$$

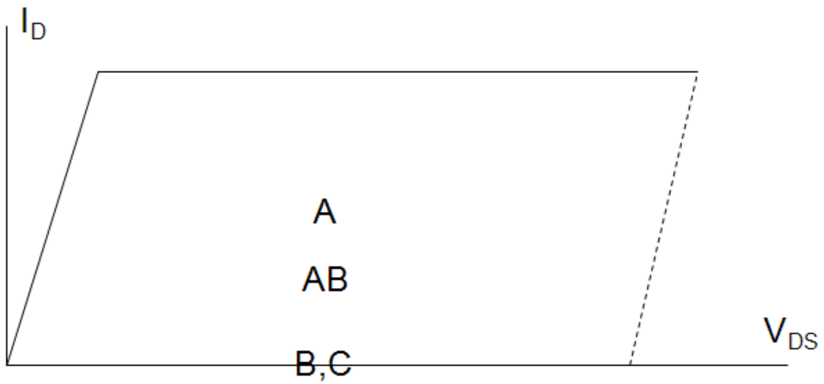
Linearity Measures

- Adjacent Channel Power Ratio (ACPR)
  - Ratio of the power in a specified band outside the signal to the RMS power in the signal*
  - Examines how nonlinearity affects adjacent channels.
- Error Vector Magnitude
  - Vector distance between desired and measured signal vector normalized by the signal amplitude
- Carrier-to-Intermodulation (C/I) Ratio
  - Measured in a two-tone intermodulation test.
  - Raab: C/I should be at least 30 dB for a linear PA.*
- Noise Power Ratio
  - Measures in-band distortion.

*Source: F. Raab, P. Asbeck, S. Cripps, P. Kenington, Z. Popovic, N. Pothecary, J. Sevic, and N. Sokal, "RF and Microwave Power Amplifier and Transmitter Topologies, Part 1," *High Frequency Electronics*, May 2003.

Amplifier Classes

- Class A:
  - Max Drain Efficiency: 50%
  - Best Intrinsic Linearity



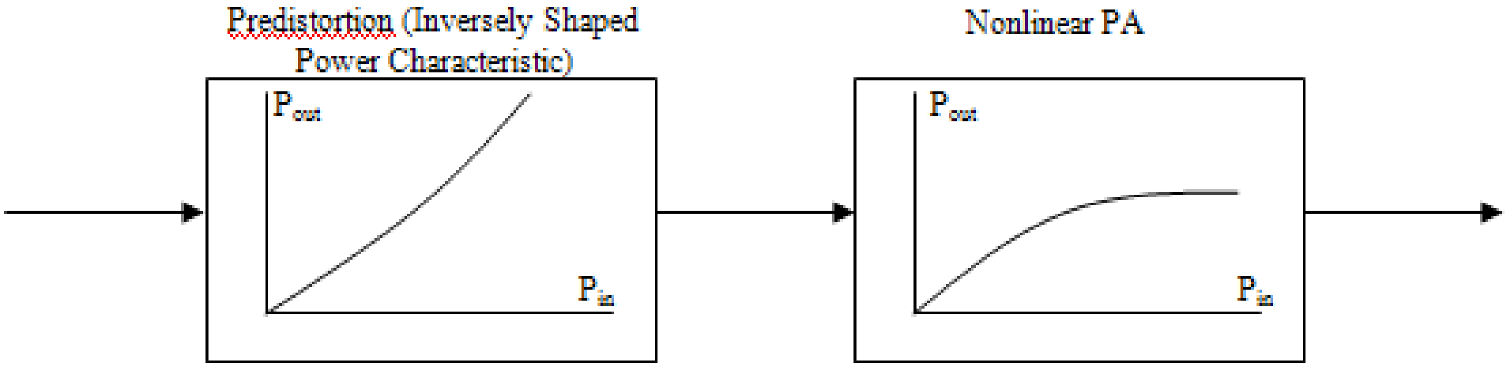
- Class B:
  - Max Drain Efficiency: 78.5%
  - Reduction of Linearity
- Class C:
  - Bias below threshold.
  - Higher efficiency but less linearity than B.
- Class E, F: Higher efficiency switching modes.

Linearity and Efficiency Configurations

- Acknowledgment: Article in *IEEE Transactions on Microwave Theory and Techniques* and 4-part series of articles in *High Frequency Electronics* by Raab *et al.* provide an excellent survey of different topologies and their advantages.
- Much information from these articles is used in this section.

Predistortion

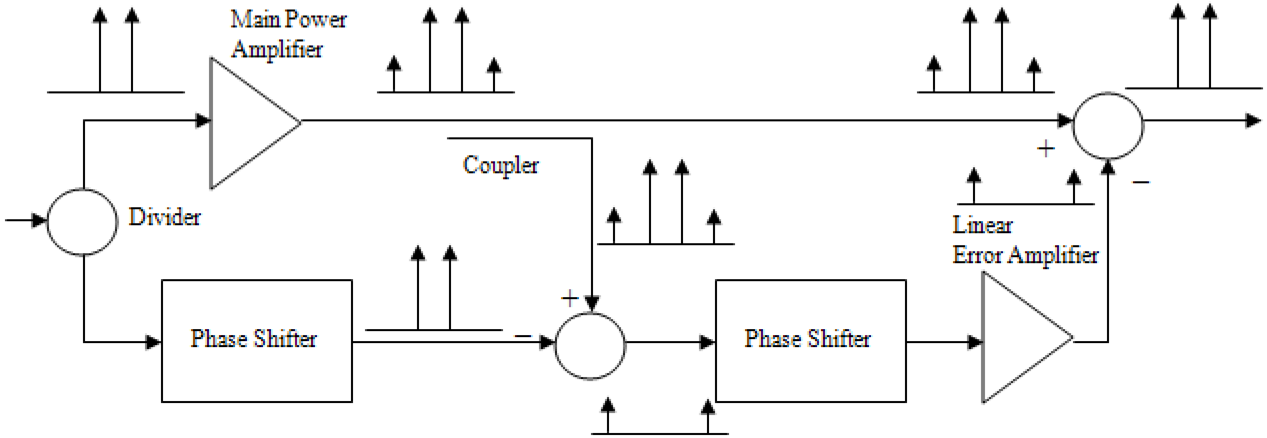
- “Uncompress” the compression by a component with an oppositely shaped compression characteristic.



- Challenging for systems with memory
- Requires adaptive lookup table → memory requirements can be large.

Feedforward

- The linear input signal is used as a reference to subtract unwanted spectral components from the output signal.

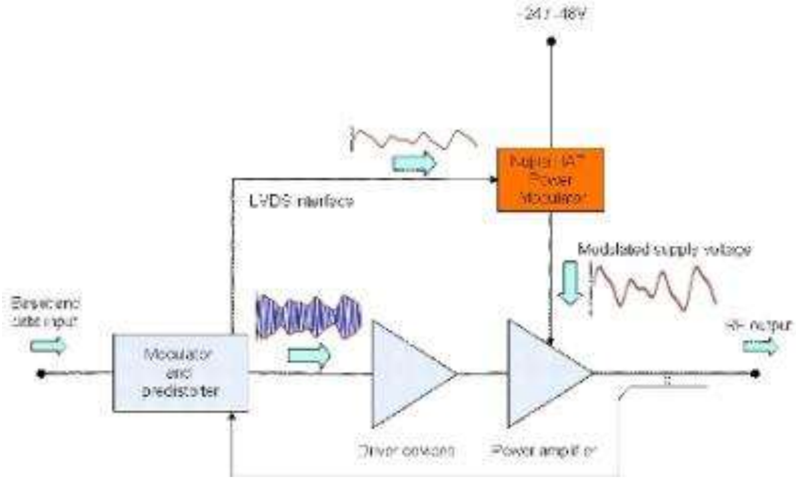


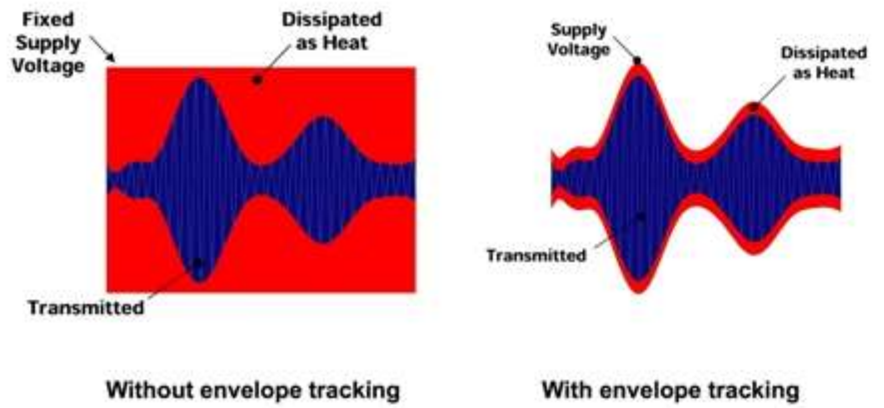
- Linear error amplifier requires additional DC power.
- Combiners also contribute to efficiency decrease.
- Drift is possible; may require a control system.

Acknowledgment: F. Raab, P. Asbeck, S. Cripps, P. Kenington, Z. Popovic, N. Pothecary, J. Sevic, and N. Sokal, “RF and Microwave Power Amplifier and Transmitter Topologies, Part 4,” *High Frequency Electronics*, November 2003.

Envelope Tracking

- The supply voltage is adjusted based on envelope amplitude.
- The efficiency is improved, but buck/boost converters require additional DC.
- Works well for high peak-to-average-power ratio (PAPR):





*Pictures reprinted from G. Wimpenny, "Improving Multi-Carrier PA Efficiency Using Envelope Tracking," *RF Engineer Network*, http://www.rfengineer.net, April 2009.

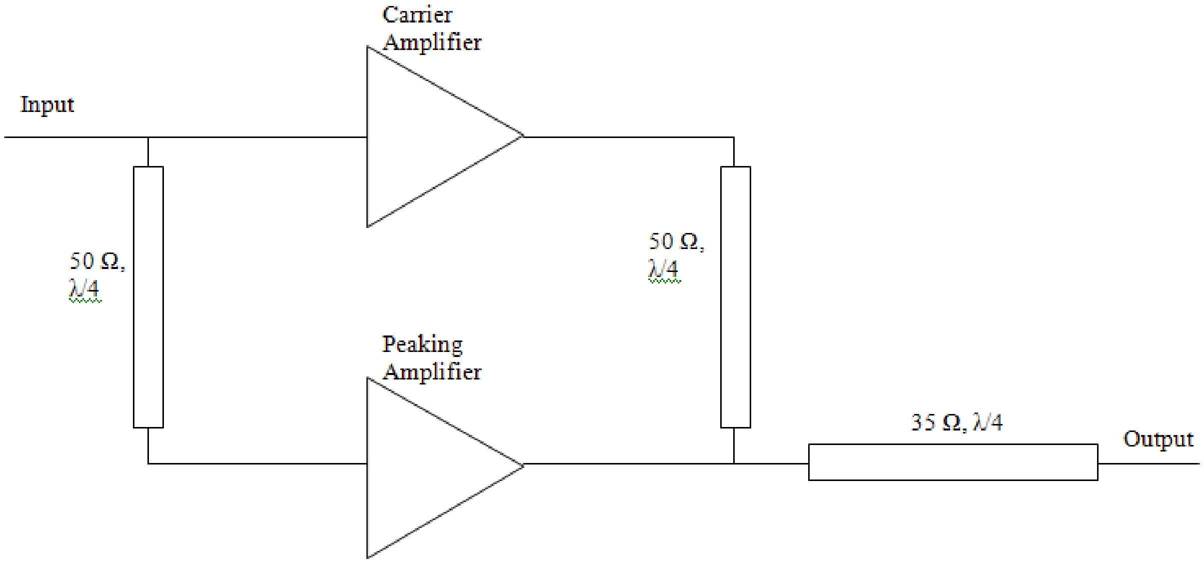
Additional Source: F. Raab *et* al., "Power Amplifiers and Transmitters for RF and Microwave" *IEEE Transactions on Microwave Theory and Techniques*, pp. 814-826, Vol. 50, No. 3, March 2002.

Envelope Elimination and Restoration (Kahn Technique)

- The amplitude modulation is removed from the signal and re-inserted after the PA.
- Allows the amplitude to run at optimum efficiency without amplitude distortion.
- Must align amplitude and phase modulation (need low AM-to-PM conversion).*

*Source: F. Raab *et* al., IEEE *Transactions on Microwave Theory and Techniques,* Vol. 50, No. 3, March 2002.

Doherty



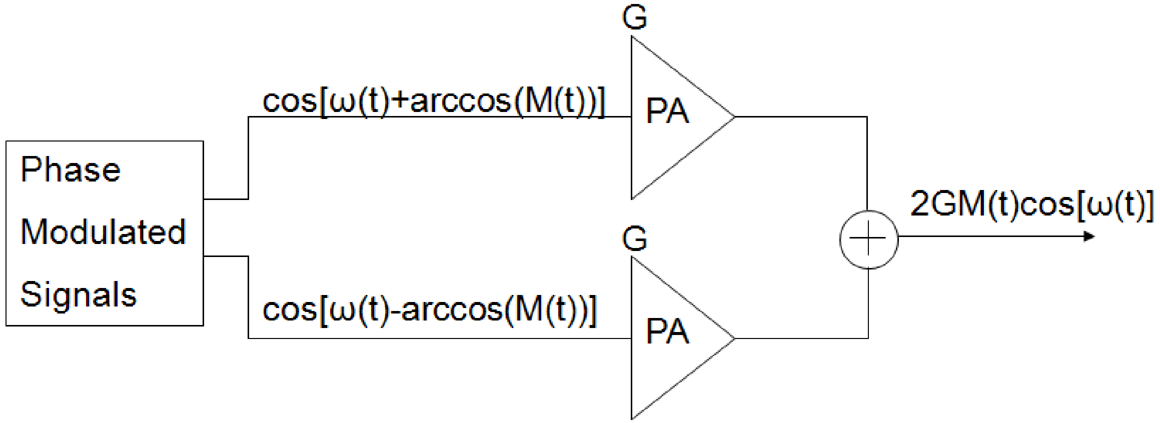
- Carrier Amplifier: Class B
- Peaking Amplifier: Class C
- Peaking amplifier turns on when the signal becomes large.
- Linearity is at Class B level from this design.

LINC (Linear Amplification with Nonlinear Components)

- The amplitude modulation M(t) is "hidden" in the phase and returned to the amplitude after the summer:

$$v_1(t) = \cos\left(\omega t + \cos^{-1}(M(t))\right)$$
$$v_2(t) = \cos\left(\omega t - \cos^{-1}(M(t))\right)$$
$$v_{out}(t) = G\cos\left(\omega t + \cos^{-1}(M(t))\right) + G\cos\left(\omega t - \cos^{-1}(M(t))\right)$$

$$v_{out}(t) = 2G\cos\omega t\cos(\cos^{-1}(M(t)) = 2GM(t)\cos\omega t$$



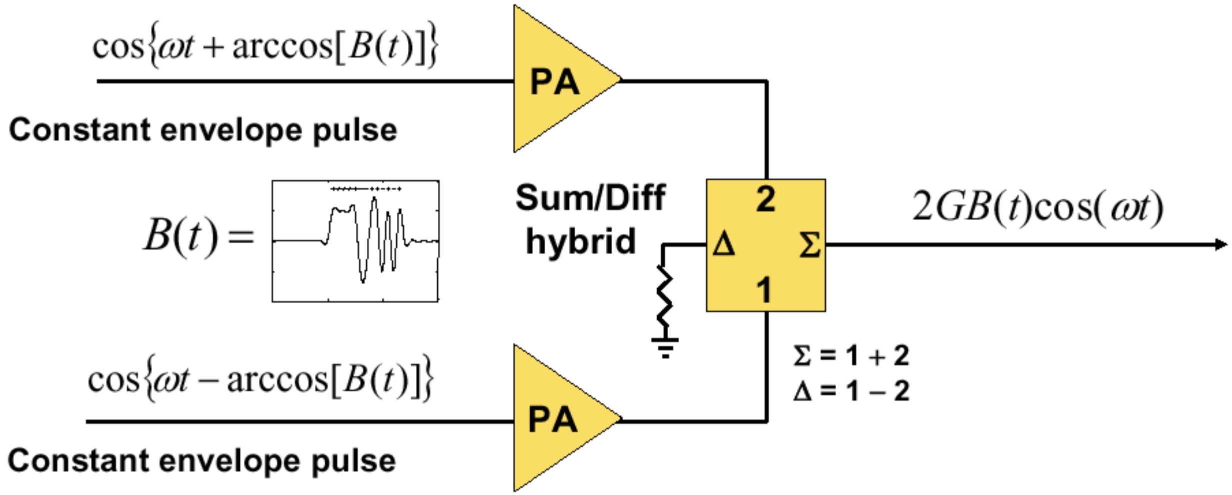
- But how can a summer be implemented?

Implementation Options

- 180-Degree Coupler
- Chireix Outphasing Combiner*
- Linearity and efficiency vary by modulation scheme for each design.
- 180-degree coupler is more robust for linearity.

*H. Chireix, “High Power Outphasing Modulation,” *Proceedings of the IRE*, Vol. 23, pp. 1370-1392, November 1935.

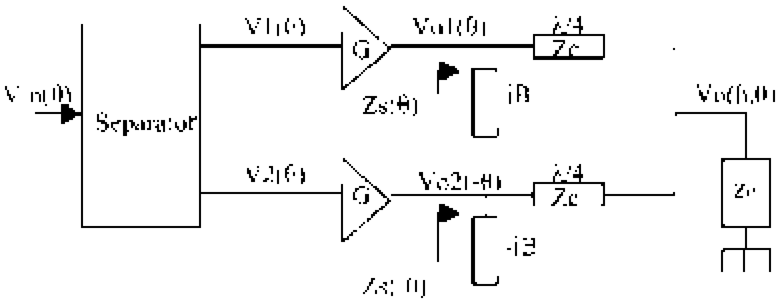
180-Degree Coupler

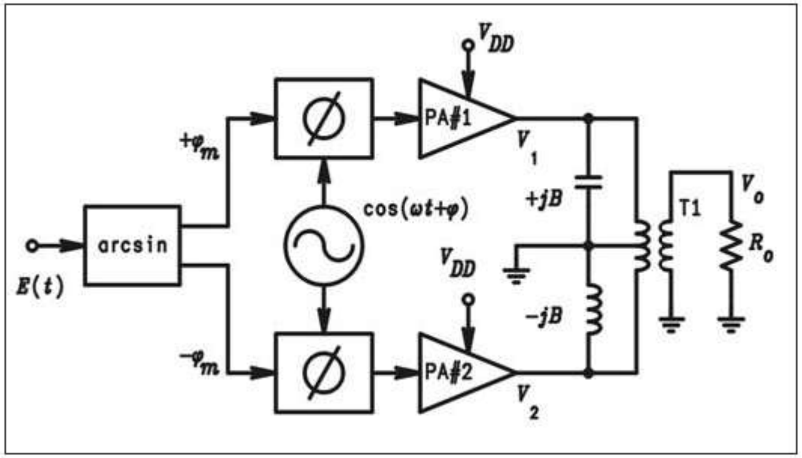


- It is matched and reciprocal.
- Power can be lost to the fourth-port termination, depending on the modulation scheme.

*Reprinted from J. de Graaf, H. Faust, J. Alatishe, and S. Talapatra, "Generation of Spectrally Confined Transmitted Radar Waveforms," Proc. IEEE Conf. on Radar, 2006, pp. 76-83

Chireix Combiner



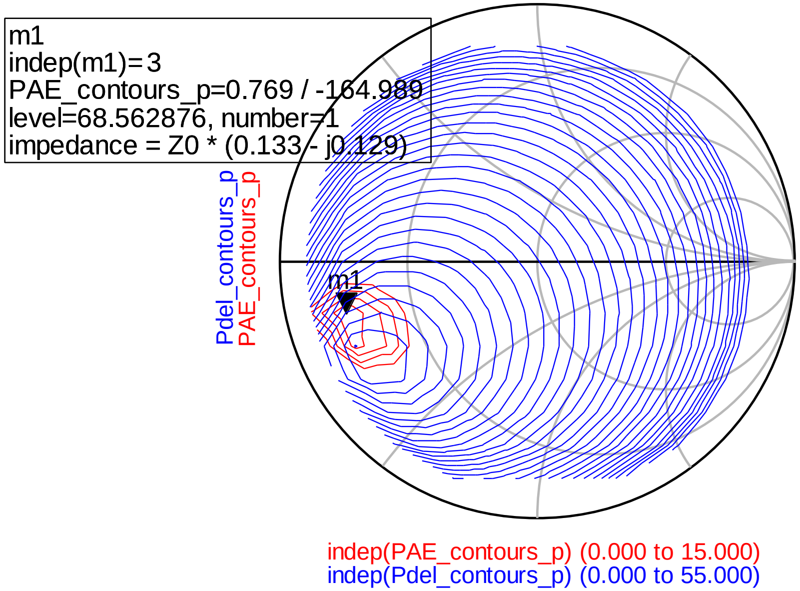


- Combiner ports are not isolated, so the impedances seen by each amplifier stage can change dynamically.

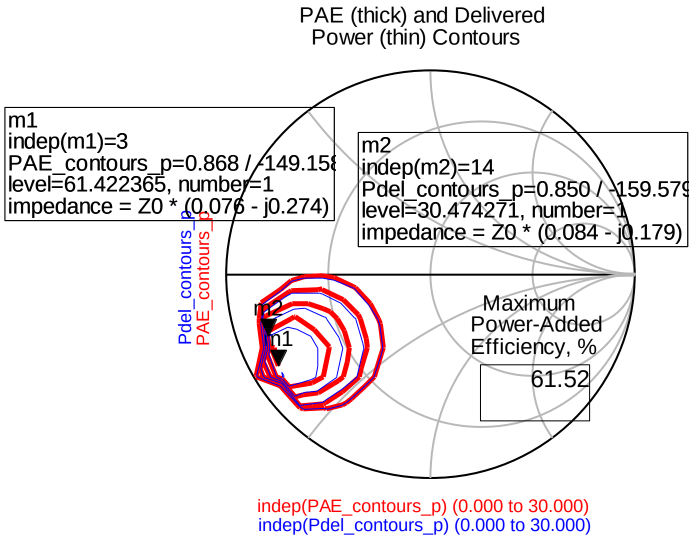
*Reprinted from F. Raab, P. Asbeck, S. Cripps, P. Kenington, Z. Popovic, N. Pothecary, J. Sevic, and N. Sokal, “RF and Microwave Power Amplifier and Transmitter Technologies, Part 1,” *High Frequency Electronics*, May 2003.

**A. Birafane and A. Kouki, “On the Linearity and Efficiency of Outphasing Microwave Amplifiers,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 52, No. 7, July 2004, pp. 1702-1708.

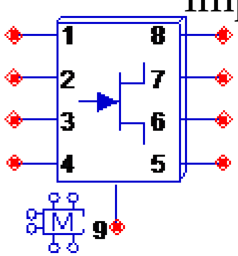
PHEMT Source/Load Pull



Load Pull: Found maximum PAE at 68.6% with a source impedance of (6.65 – j6.45)

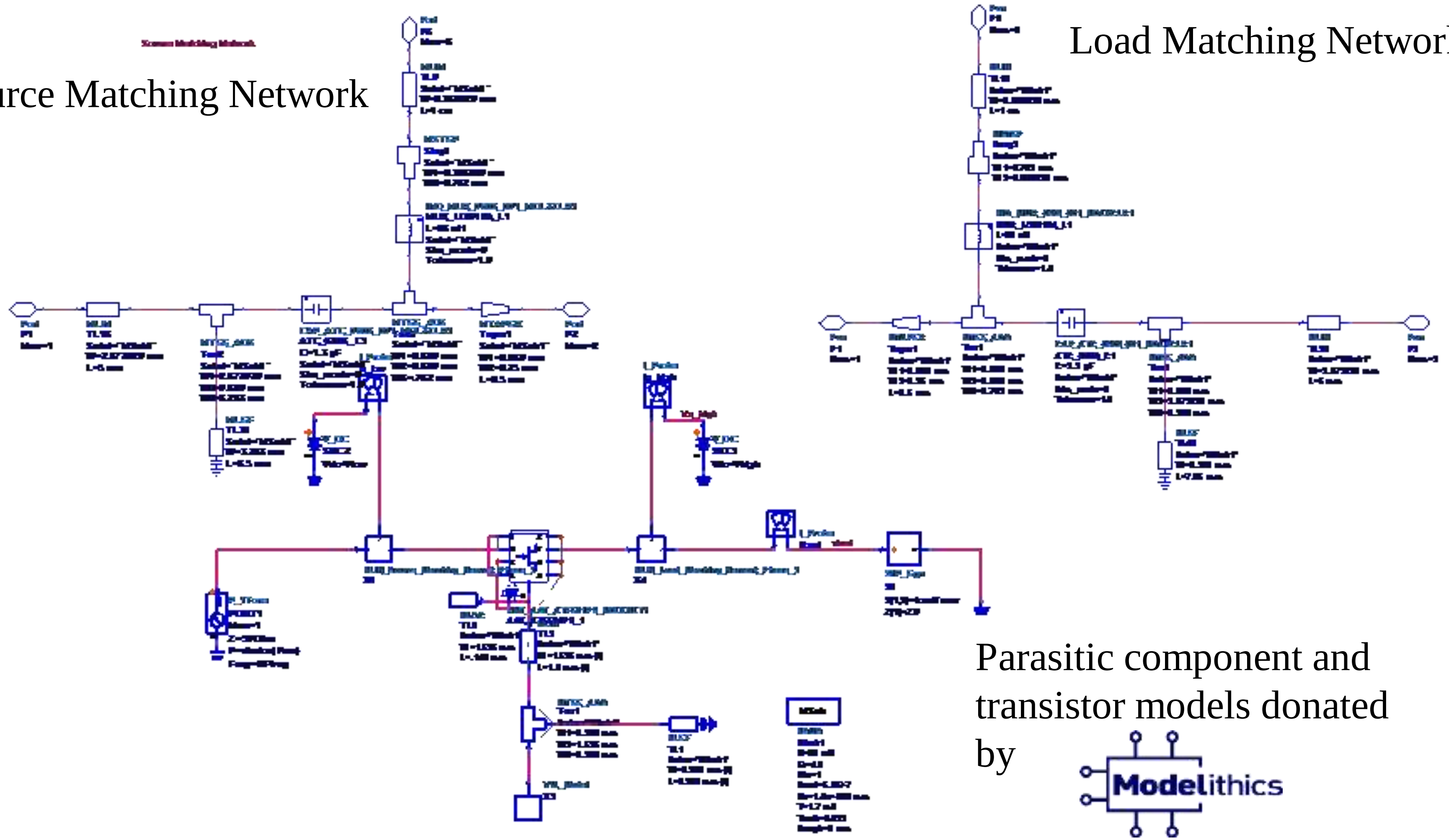


Source Pull: Found maximum PAE at 61.5% with a source impedance of (4.2 – j8.95)



Modelithics Transistor Model

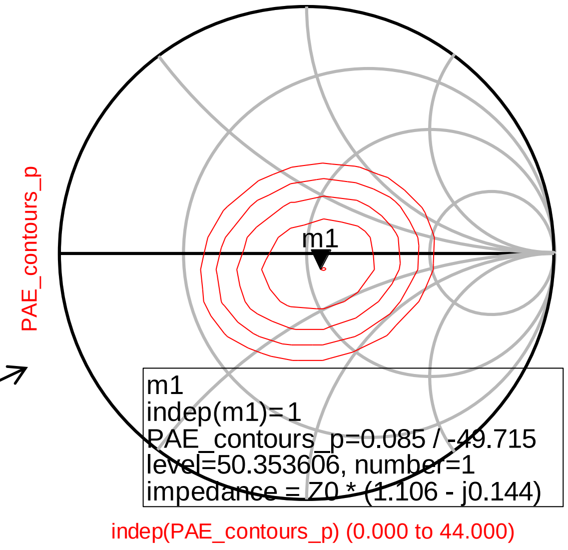
Circuit Design with Parasitic/ T-Line Models

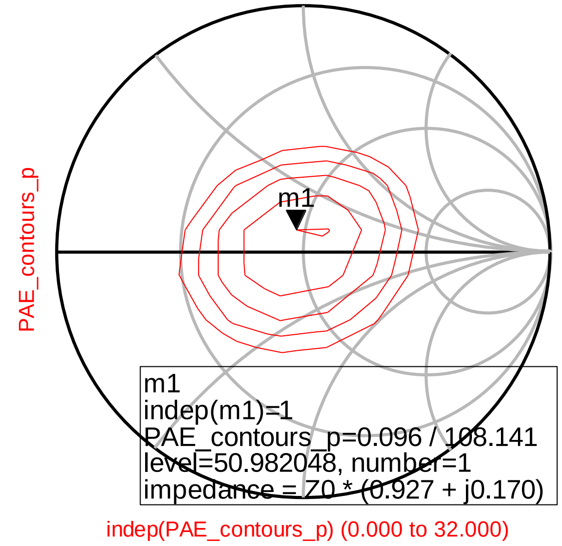


Parasitic component and transistor models donated by Modelithics

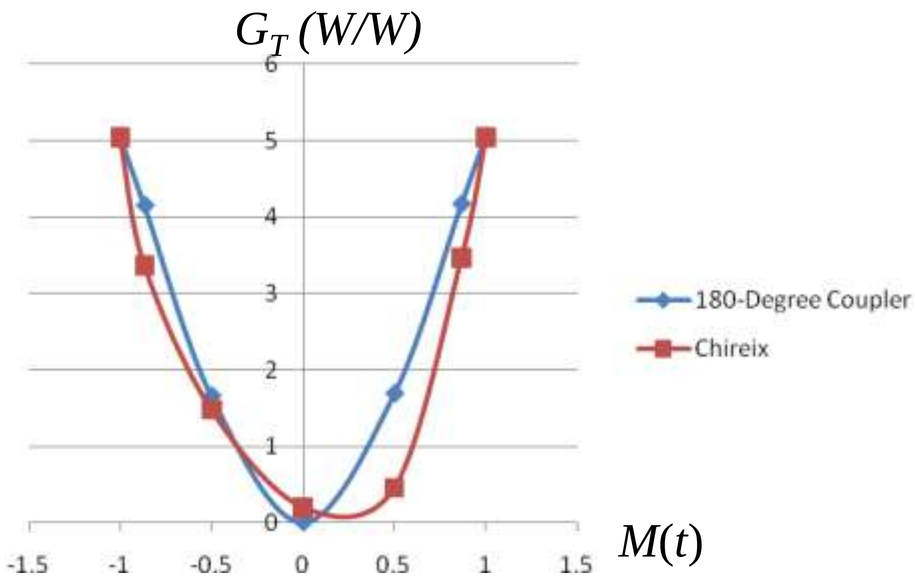
Load-Pull Efficiency Comparison

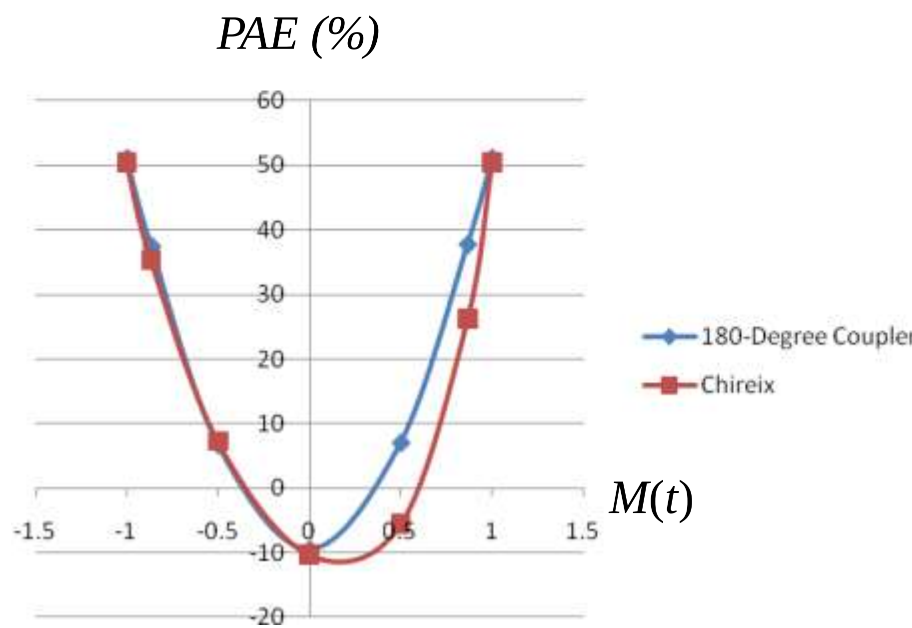
- Both Designs: Maximum Efficiency near 50 ohms
- Test with CW (M(t) = 1)
- Maximum PAE for Chireix design = 50%
- Maximum PAE for 180-degree coupler design = 51%





GaAs PHEMT Amplifier for Different $M(t)$ Levels





- 180-degree coupler is perfect parabola → Excellent linearity
- Chireix demonstrates linearity flaws.

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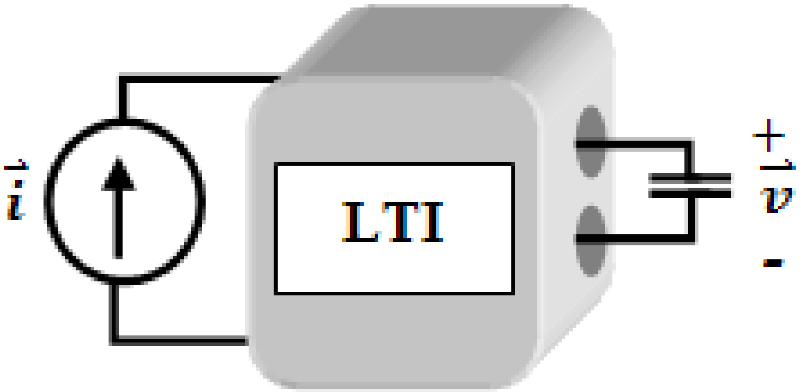
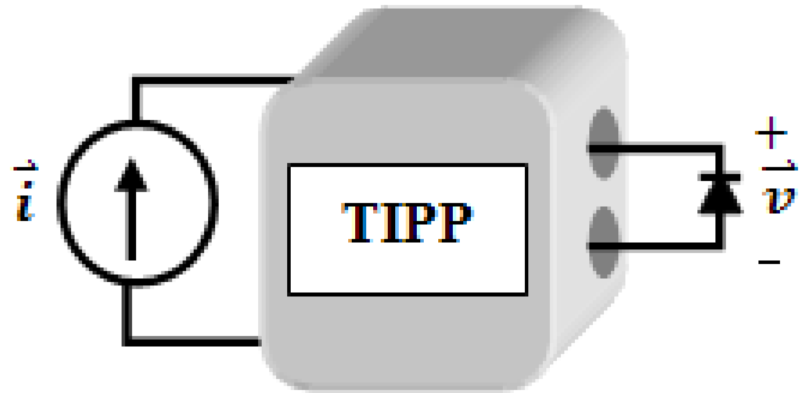
Joint Optimization: The Way Forward

- State-of-the-art approaches to improving spectral conformity have traditionally included separate examination of
  - Circuit design
  - Waveform design
- The technology and theory now exist to *simultaneously* optimize both!
- Knowing the circuit nonlinearities speeds the optimization → Wirtinger Calculus for TIPP Systems.

TIPP Systems

- Assume a time invariant periodicity preservation (TIPP) system.





LTI: All currents and voltages oscillate at the same frequency.

TIPP: All currents and voltages are periodic with the same period (harmonic levels can change).

TIPP Systems

- Assume a TIPP Operator $\mathcal{Z}$:

$$v(t) = \mathcal{Z}\{i(t)\}$$

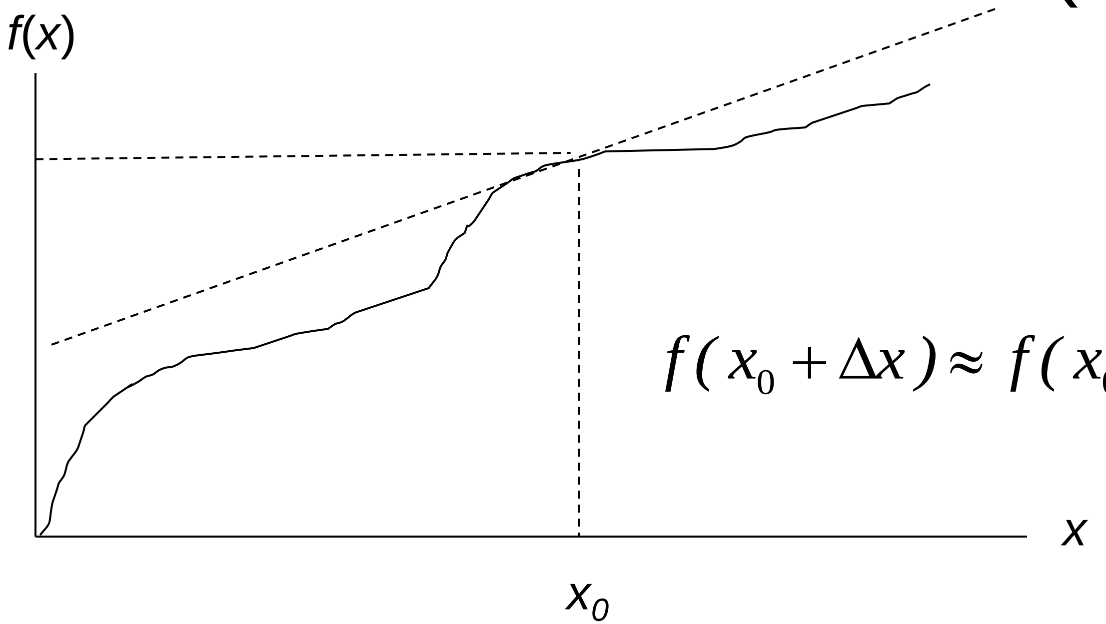
- There is a corresponding operator on the vectors of Fourier coefficients:

$$\vec{v} = \mathbf{Z}\,\vec{i}$$

- For a particular “operating point” large signal, **Z** is a matrix.

Affine Approximation

- Consider a nonlinear function *f* (*x*):



$$f(x_0+\Delta x)\approx f(x_0)+\frac{df(x_0)}{dx}\Delta x$$

- Affine approximation around the operating point of a nonlinear function

Wirtinger Calculus for TIPP Systems

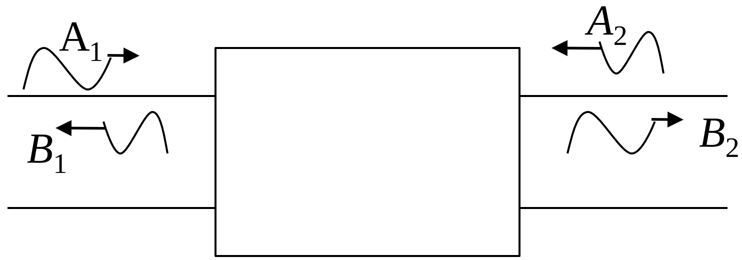
$$v(t)+\Delta v(t)\approx Z\{i(t)\}+\frac{\partial v(t)}{\partial i(t)}\Delta i(t)+\frac{\partial v(t)}{\partial i^*(t)}\Delta i^*(t)$$

- In terms of the Fourier series coefficient vectors:

$$\bar{v}+\Delta\bar{v}\approx[Z]\bar{i}+\left[J_{\bar{v}}(\bar{i})\right]\Delta\bar{i}+\left[J_{*\bar{v}}(\bar{i})\right]\Delta\bar{i}^*$$

- The TIPP parameters give an affine approximation around a nonlinear operating point.

Agilent X-Parameters[1*]



[1] X-parameters is a registered trademark of Agilent Technologies.

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

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

**C. Baylis *et al*., "Going Nonlinear," *IEEE Microwave Magazine*, April 2011.

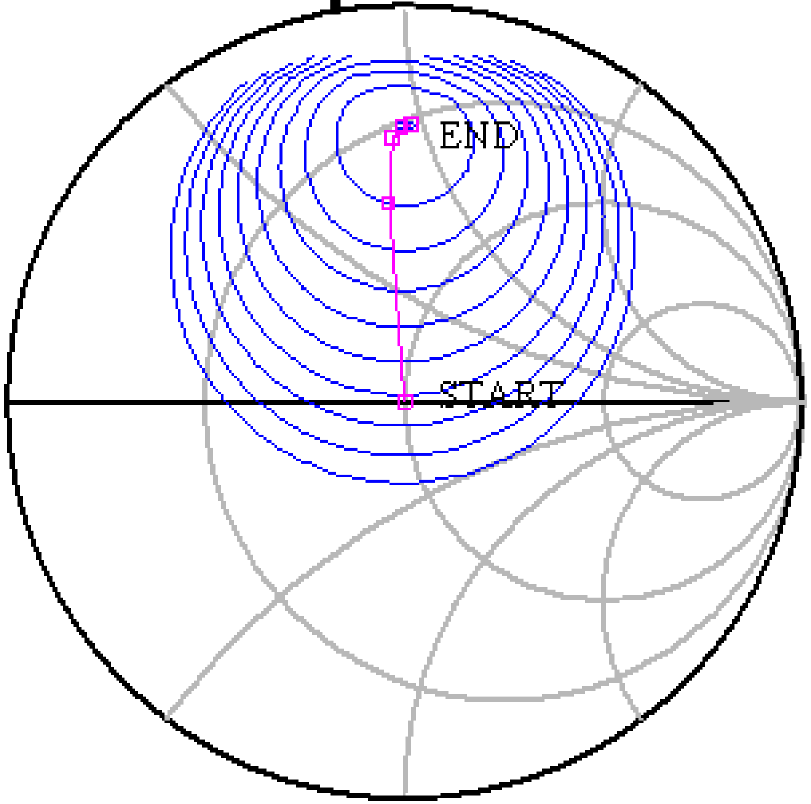
$P = e^{j\angle A_{11}}$ provides phase correction for harmonic conversion.

$$X_{ef,gh}^{(S)}$$

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.

Fast Load-Impedance Optimization Algorithm*



- Traditional:
  - 400 Γ states
  - Maximum Power = 22.76 dBm
- Steepest Ascent:
  - 17 Γ states
  - Maximum Power = 22.72 dBm
- Accurate results for small number of simulations

*C. Baylis, L. Dunleavy, S. Lardizabal, R.J. Marks II, and A. Rodriguez, "Efficient Optimization Using Experimental Queries: A Peak-Search Algorithm for Efficient Load-Pull Measurements," Accepted for Publication in *Journal of Advanced Computational Intelligence and Intelligent Informatics*, September 2010.

Conclusions

- Spectral spreading from radar systems must be mitigated, but not at the cost of system efficiency.
- Several useful design approaches exist for linearity and efficiency improvement.
- An apparent solution is in joint waveform and circuit optimization with the Wirtinger calculus.
- An approach and test platform for real-time load-pull and waveform optimization is under development at Baylor University.

Acknowledgments

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- Baylor Research Assistants: Loria Wang, Josh Martin, Matthew Moldovan, Hunter Miller, Robert Scott
- This work has been supported in part by a Young Investigator Grant and two Undergraduate Research and Scholarly Achievement Grants from the Baylor University Vice Provost for Research.
- Agilent Technologies, for cost-free loan of the Advanced Design System software.
- Maury Microwave for donation of ATS Software DLL Libraries.
- Modelithics, Inc., for donation of model libraries.
- Raytheon (sponsorship) and Maury Microwave for Load-Pull Algorithm Support (in-kind support)
- Larry Cohen, Jean de Graaf, and Dr. Eric Mokole, U.s. Naval Research Laboratory, for collaboration.

References

- C. Baylis, L. Dunleavy, S. Lardizabal, R.J. Marks II, and A. Rodriguez, "Efficient Optimization Using Experimental Queries: A Peak-Search Algorithm for Efficient Load-Pull Measurements," Accepted for Publication in *Journal of Advanced Computational Intelligence and Intelligent Informatics*, September 2010.
- J. de Graaf, H. Faust, J. Alatishe, and S. Talapatra, "Generation of Spectrally Confined Transmitted Radar Waveforms," Proceedings of the IEEE Conference on Radar, 2006, pp. 76-83.
- J. de Graaf, Personal Interaction.
- S. Cripps, *RF Power Amplifiers for Wireless Communications*, Artech House, 1999.
- F. Raab, P. Asbeck, S. Cripps, P. Kenington, Z. Popovic, N. Pothecary, J. Sevic, and N. Sokal, "RF and Microwave Power Amplifier and Transmitter Technologies, Part 1," *High Frequency Electronics*, May 2003.
- F. Raab, P. Asbeck, S. Cripps, P. Kenington, Z. Popovic, N. Pothecary,
- J. Sevic, and N. Sokal, "RF and Microwave Power Amplifier and Transmitter
- Topologies, Part 4," *High Frequency Electronics*, November 2003.
- K. Mekechuck, W. –J. Kim, S. Stapelton, and J. Kim, "Linearizing Power Amplifiers Using Digital Predistortion, EDA Tools, and Test Hardware," *High Frequency Electronics*, April 2004, pp. 18-27.
- F. Raab, P. Asbeck, S. Cripps, P. Kenington, Z. Popovich, N. Pothecary, J. Sevic and N. Sokal, "RF and Mircowave Power Amplifier and Transmitter Technologies, Part 4," *High Frequency Electronics,* November 2003.

References, cont.

- C. Baylis, L. Wang, M. Moldovan, J. Martin, H. Miller, L. Cohen, and J. de Graaf, "Spectrum Issues in Power Amplifier Design," 2010 IEEE Waveform Diversity Conference, Niagara Falls, Ontario, Canada, August 2010.
- D. Pozar, *Microwave Engineering*¸ Third Edition, John Wiley and Sons, 2005.
- A. Birafane and A. Kouki, "On the Linearity and Efficiency of Outphasing Microwave Amplifiers," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 52, No. 7, July 2004, pp. 1702-1708.
- F. Raab, "Efficiency of Outphasing RF Power-Amplifer Systems," *IEEE Transactions on Communications*, Vol. 33, No. 10, October 1985.
- G. Wimpenny, "Improving Multi-Carrier PA Efficiency Using Envelope Tracking," RF Engineer Network, http://www.rfengineer.net, April 2009.
- Application Note AN-005: "2.5-2.7 GHz 20 W Doherty Amplifier for WiMAX Applications Using the NPT25100," January 2008.
- F. Raab, P. Asbeck, S. Cripps, P. Kenington, Z. Popovic, N. Pothecary, J. Sevic, and N. Sokal, "Power Amplifiers and Transmitters for RF and Microwave," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 50, No. 3, March 2002.
- C. Baylis, M. Moldovan, L. Wang, and J. Martin, "LINC Power Amplifiers for Reducing Out-of-Band Spectral Re-growth: A Comparative Study," 2010 IEEE Wireless and Microwave Technology Conference (WAMICON 2010), Melbourne, Florida, April 2010.
- Agilent Technologies, Santa Rosa, California: http://www.agilent.com.

References, cont.

- W. Wirtinger, “Zur Formalen Theorie der Funktionen von mehr Complexen Veranderlichen,” Math. Ann., 97, 357-75, 1927.
- D. Root, “A New Paradigm for Measurement, Modeling, and Simulation of Nonlinear Microwave and RF Components,” Presentation at Berkeley Wireless Research Center, April 2009.
- G. Pailloncy, F. Verbeyst, and M. Vanden Bossche, “Nonlinear Extensions for VNAs: Quid Pro Quo?”, *Microwave Journal*, Vol. 52, No. 9, September 2009.
- M. Myslinski, F. Verbeyst, M. Vanden Bossche, and D. Schreurs, “S-Functions Extracted from Narrow-Band Modulated Large-Signal Network Analyzer Measurements,” 74th Automatic RF Techniques Group Conference, 2009.
- F. Verbeyst and M. Vanden Bossche, “VIOMAP: The S-Parameter Equivalent for Weakly Nonlinear RF and Microwave Devices,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 42, No. 12, December 1994, pp. 2531-2535.
- P. Tasker, “Practical Waveform Engineering,” *IEEE Microwave Magazine*, Vol. 10, No. 7, pp. 65-76, December 2009.
- D. Root, J. Horn, L. Betts, C. Gillease, and J. Verspecht, “X-Parameters: The New Paradigm for Measurement, Modeling, and Design of Nonlinear RF and Microwave Components,” Microwave Engineering Europe, 2008.
- G. Gonzalez, *Microwave Transistor Amplifiers: Analysis and Design*, Second Edition, Prentice-Hall, 1997.

References, cont.

- D. Vye, “Fundamentally Changing Nonlinear Microwave Design,” *Microwave Magazine*, March 2010, pp. 22-44.
- J. Verspecht, D. Williams, D. Schreurs, K. Remley, and M. McKinley, “Linearization of Large-Signal Scattering Functions,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 53, No. 4, April 2005, pp. 1369-1376.
- J. Verspecht and D. Root, “Polyharmonic Distortion Modeling,” *IEEE Microwave Magazine*, June 2006, pp. 44-57.
- Eleanor Chin-hwa Chu, *Discrete and Continuous Fourier Transforms: Analysis, Applications and Fast Algorithms*, Chapman and Hall/CRC (2008), pp.314-320.
- E. Saff and A. Snider, *Fundamentals of Complex Analysis with Applications to Engineering and Science,* Third Edition, Pearson Education Inc., 2003.
- R.J. Marks II, *Handbook of Fourier Analysis and Its Applications* (Oxford University Press, 2009).
- D. Schreurs, J. Verspecht, B. Nauwelaers, A. Van de Capelle, M. Van Rossum, “Direct Extraction of the Non-Linear Model for Two-Port Devices from Vectorial Non-Linear Network Analyzer Measurements,” 27th European Microwave Conference Digest, September 1997, pp. 921-926.
- Applied Wave Research, El Segundo, California: http://web.awrcorp.com.

References, cont.

- J. Verspecht, J. Horn, L. Betts, D. Gunyan, R. Pollard, C. Gillease, and D. Root, "Extension of X-Parameters to Include Long-Term Dynamic Memory Effects," 2009 International Microwave Symposium Digest, June 2009, Boston, Massachusetts, pp. 741-744.
- J. Verspecht, J. Horn, and D. Root, "A Simplified Extension of X-Parameters to Describe Memory Effects for Wideband Modulated Signals," Automatic RF Techniques Group (ARFTG) Conference, May 2010, Anaheim, California.
- J. de Graaf, H. Faust, J. Alatishe, and S. Talapatra, "Generation of Spectrally Confined Transmitted Radar Waveforms," Proceedings of the IEEE Conference on Radar, 2006, pp. 76-83.
- C. Baylis, L. Wang, M. Moldovan, J. Martin, H. Miller, L. Cohen, and J. de Graaf, "Designing for Spectral Conformity: Issues in Power Amplifier Design," IEEE Waveform Diversity Conference, Niagara Falls, Ontario, Canada, August 2010.
- G. Simpson, "High Power Load Pull with X-Parameters – A New Paradigm for Modeling and Design," IEEE Wireless and Microwave Technology Conference, Melbourne, Florida, April 2010.
- C. Baylis, R.J. Marks II, J. Martin, H. Miller, and M. Moldovan, "Going Nonlinear," *IEEE Microwave Magazine*, Vol. 12, No. 2, April 2011, pp. 55-64.