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A Low-Budget Approach to Harmonic Load-Pull Measurements for RFPA Design

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1- Summary

- **1 Discussion:**

  - Isn't "Loadpull" a euphemism for empirical design?
  - Hasn't CAD simulation superseded old-fashioned empirical design methods?

- **2 Loadpull Systems**

  - Passive/active
  - Calibration

- **3 "DIY" Loadpull Systems**

  - Considerations
  - Results

2- CAD for HPAs

- Accurate non-linear modelling of high power microwave devices is still a developing area
- Every microwave conference has many papers on modelling, which are usually worthless to the HPA designer working in industry
- Reasons……

3 – Device Modelling Papers

- Papers on microwave device models usually based on “tiny” devices, frequently <100mW
- Inadequate information available for model implementation in commercial CAD software products
- The “***spots-on-lines***” effect; a measurement-based model is *very good* at predicting the measured characteristics *upon which it was based*!
- ***“Verification” should take the form of a fully realised amplifier. NOTHING LESS!***

4 – PA Design using CAD

- A good PA design needs to realise the power capability of the device, with good linearity and efficiency for a specified complex modulated signal
- Even if you have a good model for an RF power device, you still have to design input and output matching circuits. *The CAD simulator does not tell you which topology to use*!
- Accurate modelling of all the non-linear effects in a device, together with “complex” input excitation, push CAD simulators to their limits; convergence problems are very common, especially if input and feedback capacitance parasitics have voltage dependency (varactors)

5 – The Loadpull Advantages

- A loadpull system is in effect an “Analog Simulator”!
- As with most analog techniques, it has the benefit of speed
- A device can be simulated under representative excitations (modulated signals) , so that bias and tuning conditions can be explored in order to find optimum tradeoffs between power, efficiency and linearity
- Fundamental and harmonic terminations, at *both input and output*, have a major effect on ALL of the above!

6 – Loadpull , the downside (-1)

- The success and utility of any loadpull system is strongly dependent on the skills of the operator
- This applies whether or not the system is automated ……
- The trend towards more automated systems CAN become a trend for generating too much information on too many pages in too many reports……
- “Skilled operators” cost more than the equipment

7 – Loadpull , the downside (-2)

- **The cost!…….especially with load- and source-pull**
  - Although vendors typically compare the cost of a “turnkey” loadpull system with equipment such as network analysers (x3?) and/or spectrum analysers (x2?) this is not really a fair comparison, due to the much wider utility of such instruments in both development and production areas.
- **Operator skill**
  - This has already been mentioned, but it is an important factor, both in overall cost and quality of return.

8 – Loadpull , the downside (-3)

- **Technical**

  - Calibration; especially losses, can lead to optimistic results as compared to final circuit implementation
  - Harmonic environment obtained using loadpull system may be difficult, or impractical, to realise in an economical circuit board design……
  - …..especially if data is taken at spot frequencies

9 – Loadpull Systems (-1)

- **Passive**
  - ”Traditional” approach; basically “tuners”
  - But “Traditional” systems were fundamental tuning only
  - Tuning harmonics independently from fundamental poses challenges, especially at minimum loss
  - PA designers tend to be very suspicious when tuner loss corrections exceed 1dB!
  - Most passive harmonic tuner configurations involve fundamental loss corrections >>1dB, and are severely limited in harmonic Γ (Γ close to 1 desirable and practical using circuit board matching)
  - Complex modulated signal excitation can be used directly, for ACP, BER, to explore efficiency tradeoffs

10 – Loadpull Systems (-2)

- **Active**
  - Although quite old in concept, still regarded as “radical” approach by RF engineers
  - In principle, amplitude and phase control of the harmonic generators gives independent harmonic impedance setting
  - Generator power levels can be adjusted to allow measurements to be referenced directly to device plane (eg wafer probes)
  - Lossy elements such as directional couplers can be placed in signal line to monitor RF voltage and current, allowing device diagnostics and enabling direct impedance measurements (eg, Cardiff University system)

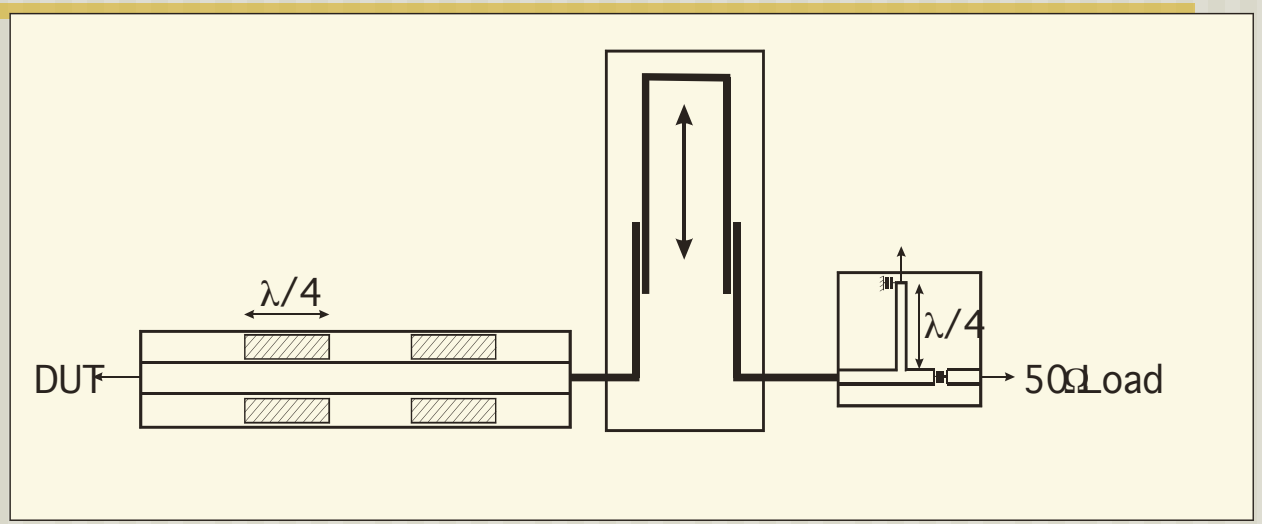
11 – DIY Loadpull (-1, Considerations)

- The cost of a turnkey loadpull system is prohibitive for most small companies (and in some cases, even big companies)
- Contract loadpull services can be purchased , but day-to-day availability is a big advantage
- Unlike mainstream test equipment, loadpull is highly specialised and will always need operators with special skills and insight. This opens up some possibilities for “DIY”

12 – DIY Loadpull (-2, requirements)

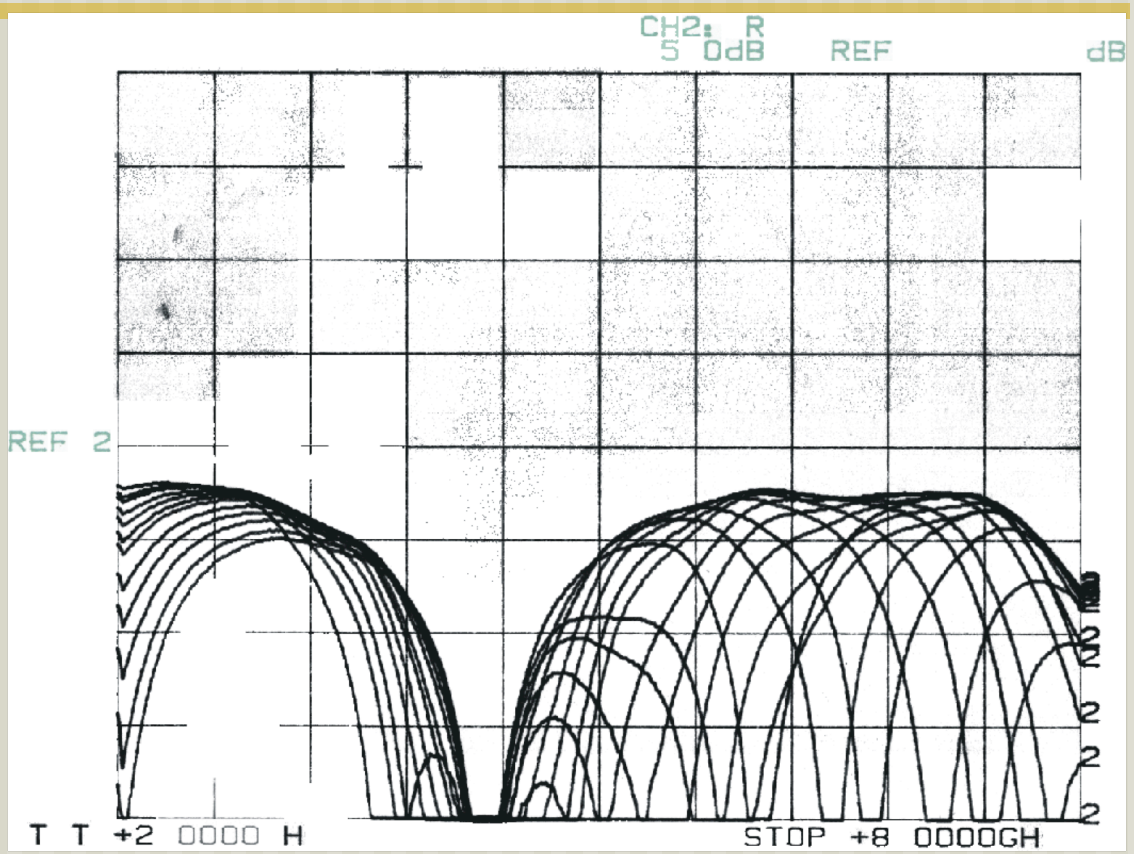
- Passive system, manual tuners (CAD drivers slow and "stupid"……..I'm a good ol' fashioned tweaker)
- Fundamental (all G, all F) and second harmonic (High G, all F) *both input and output*
- "Reasonable" independence of harmonic and fundamental tuning
- 3rd harmonic output tuning a possible option
- 1dB max loss correction in output path
- Waveform monitoring desirable (*qualitative* initially)

13 – DIY Loadpull (-3, details)



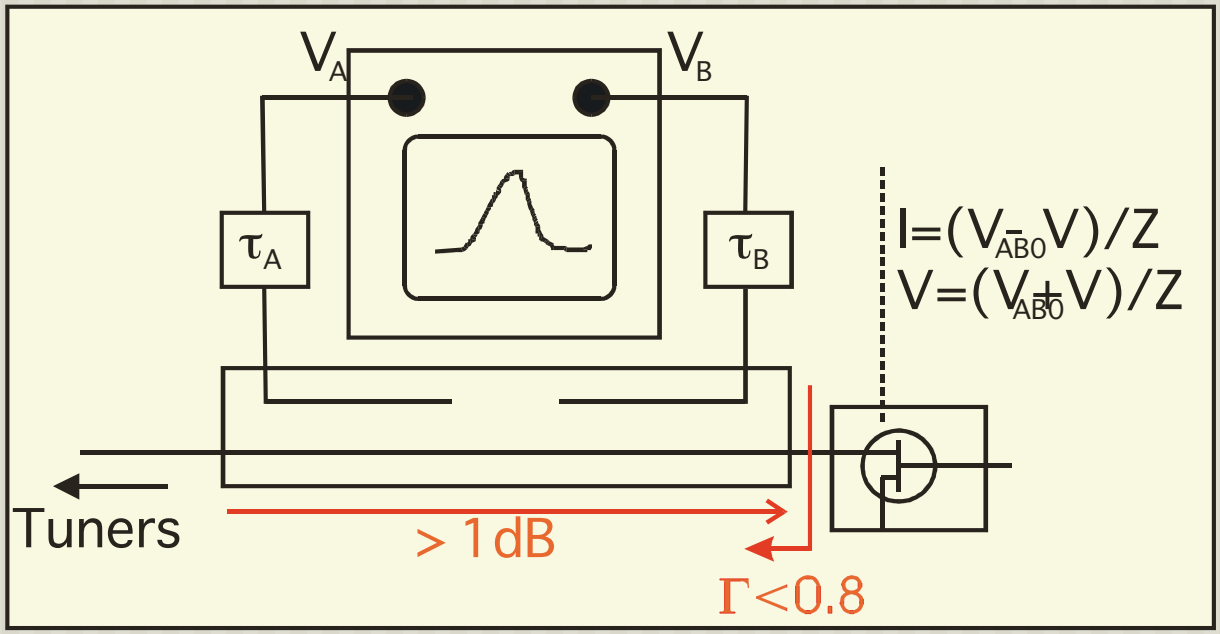
- Fundamental tuners made using 7mm co-axial airline with l /4 dielectric tuning slugs (machining costs about $300, excluding APC-7 connectors which were removed from surplus items)
- 2H tuning realised using outboard line stretcher and harmonic reflection filter
- Line stretchers removed from surplus HP 8742/8409 transmission-reflection test sets (0.25dB total loss up to 8GHz)
- Total loss at 2GHz <1dB; (estimate 1.3dB with 3rd harmonic section)

14 – DIY Loadpull (-4, tuner sweep)



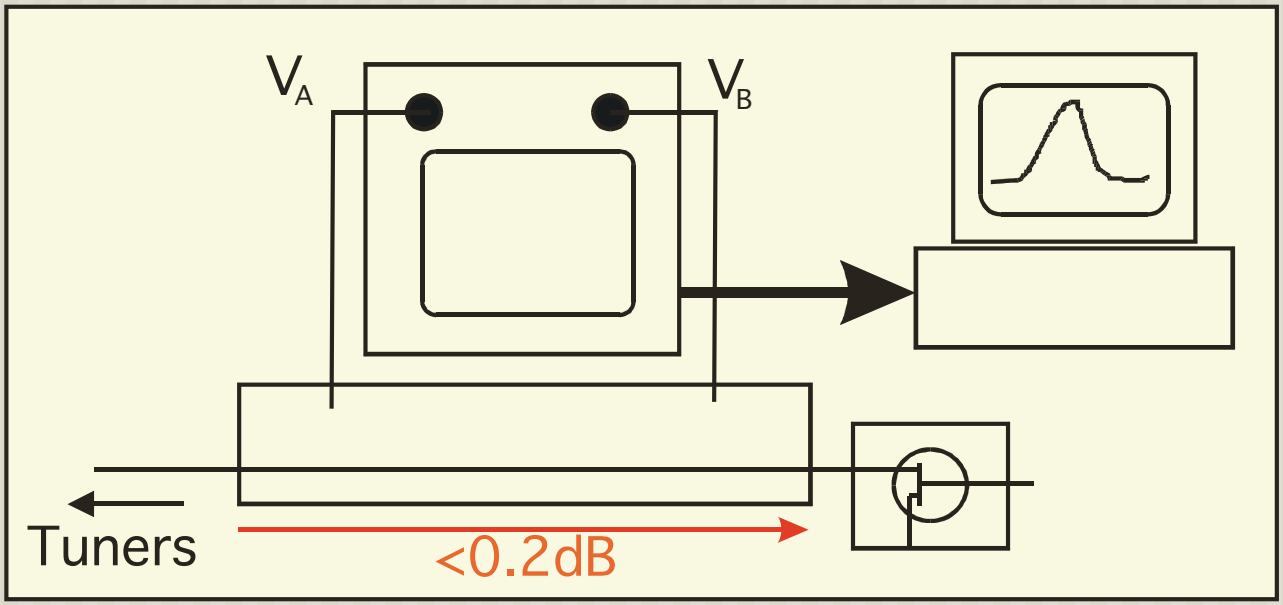
- Twin slug tuner shows 2GHz reflection varied up to a limit of 2dB return loss (limited by slug dielectric) with a constant transmission window at 4GHz

15 – Waveform Measurement (-1)



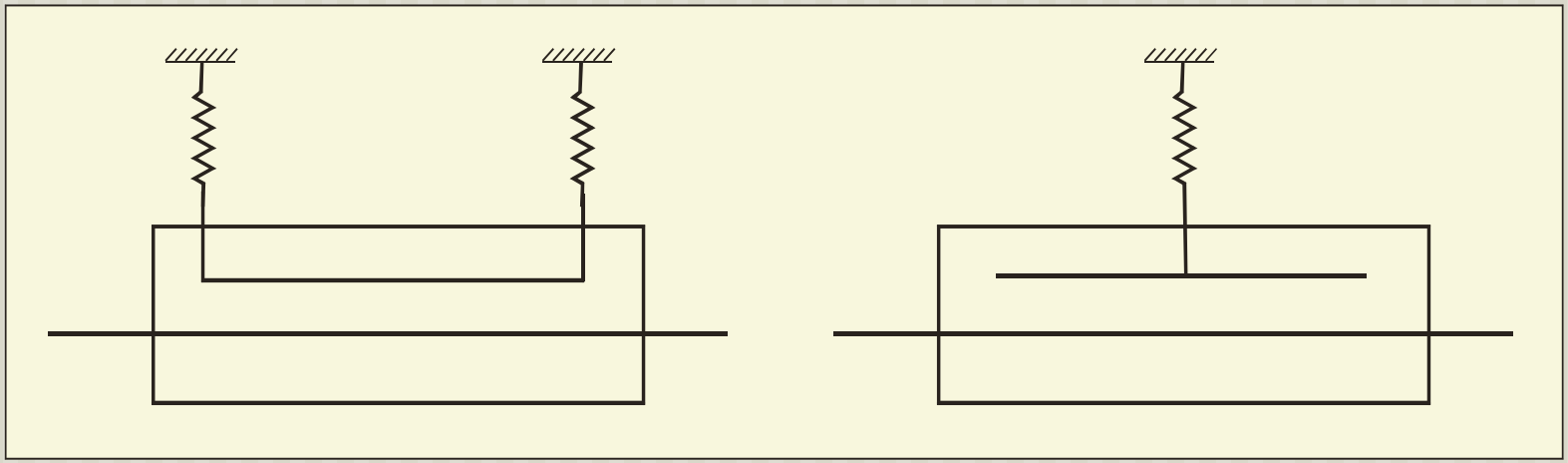
- Dual directional couplers in principle allow “real-time” waveform observation, but in practice on-line calibration of coupler, signal delays, and DUT fixture properties required
- Coupler losses (1.5dB at VERY best) are BIG problem for passive LP systems appear in front of tuners giving unacceptable reduction in maximum G values

16 – Waveform Measurement (-2)



- A pair of voltage probes, suitably spaced, present a possible alternative with *much lower* (negligible) insertion loss
- The challenge is to come up with a voltage probe with reasonably flat broadband performance and which responds to voltage alone (no magnetic field response) and which has suitably precise spatial discrimination

17 – Waveform Measurement (-3)

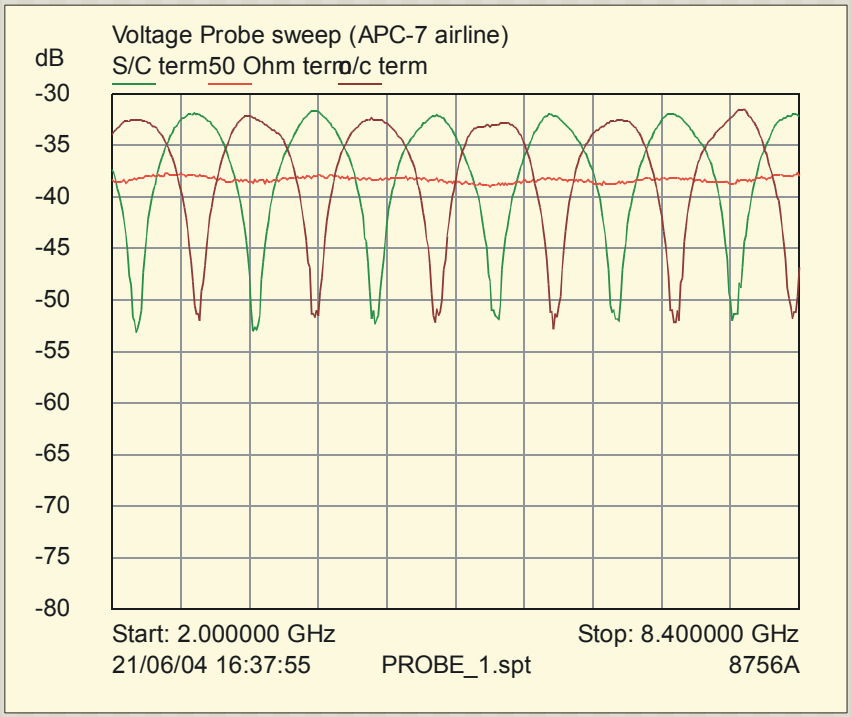


- A tale of two couplers; conventional directional coupler (left) has antisymmetric response at the two terminations, depending on direction of wave on main line
- Symmetrical coupler (left) is little used, but has identical response for forward or reverse waves
- Further analysis shows response of symmetrical coupler is proportional to voltage *at the midpoint*

18 – Waveform Measurement (-4)

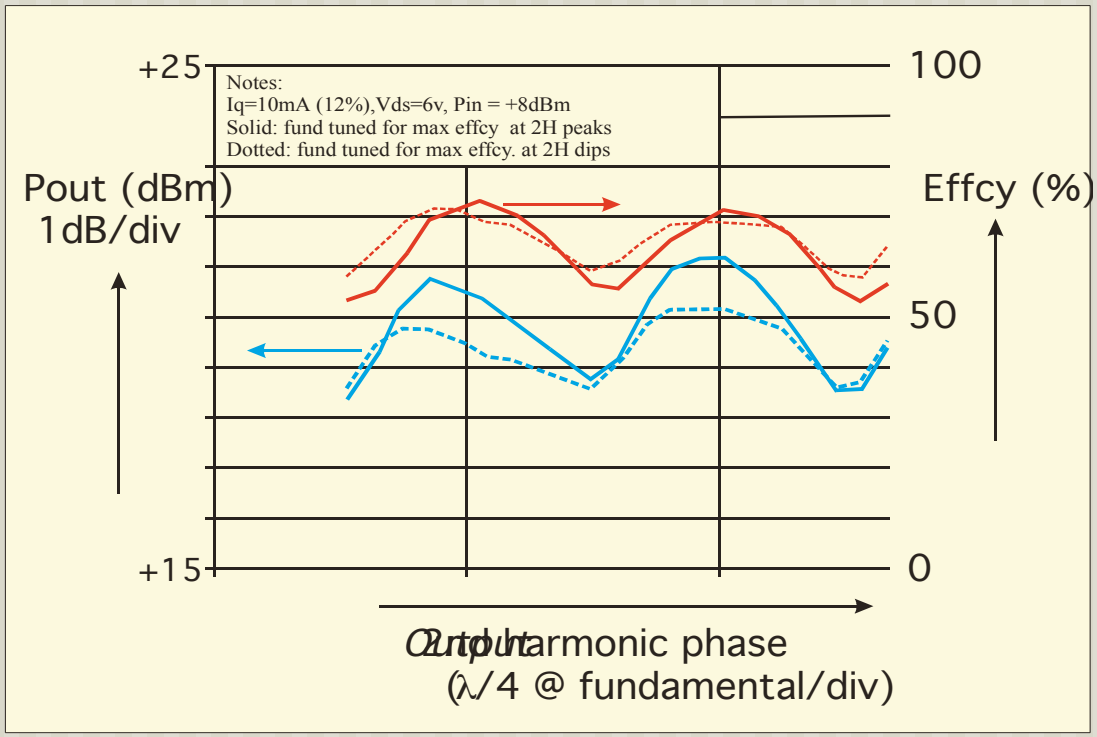
- Three incorrect statements:
  - More than 2 probes are needed (*not if phase information is extracted using sampling scope; slotted lines use amplitude detection only*)
  - A voltage probe will always have some magnetic coupling (*see previous slide*)
  - A voltage probe has a spatial resolution limited by its physical coupling dimensions (*see previous slide*)

19 – Waveform Measurement (-5)



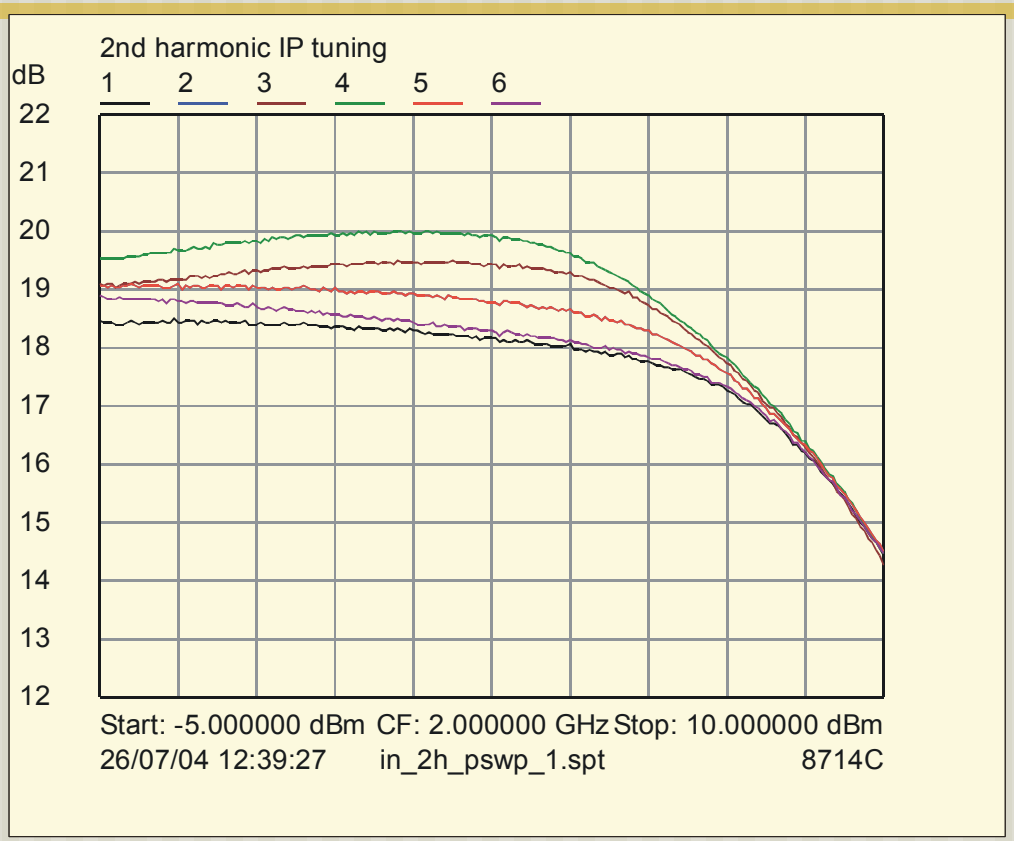
- Swept frequency response of voltage probe
- Open and short circuited terminations show expected response based on probing line at single point
- Thru response very flat

20 – Results (-1)



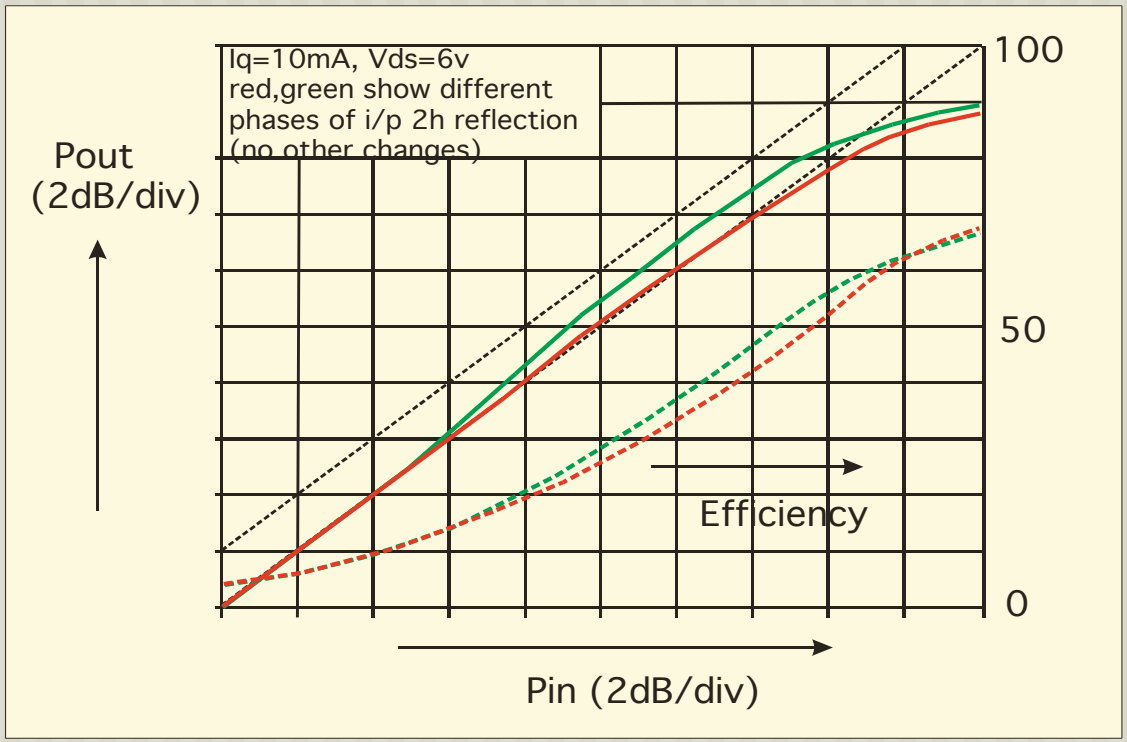
- Power and efficiency plots as output 2nd harmonic reflection is varied over full wavelength (solid)
- Dotted trace shows attempt to retune fundamental ant 2H minimum

21 – Results (-2)



- Swept power plots showing output power for a range of INPUT 2nd harmonic reflection settings
- Note substantial change in linearity due to 2H INPUT setting

22 – Results (-3)



- Swept power plots showing output power and efficiency plots for two INPUT 2nd harmonic reflection settings
- Note substantial change in linearity due to 2H INPUT setting

23 – Conclusions

- Loadpull is GREAT! The more you measure, the more you find; we should all have one!
- Models are just playing catchup
- PA Loadpull systems require input and output fundamental and harmonic tuning
- Operator skill is an important cost and logistic consideration in the “make-or-buy” management decision