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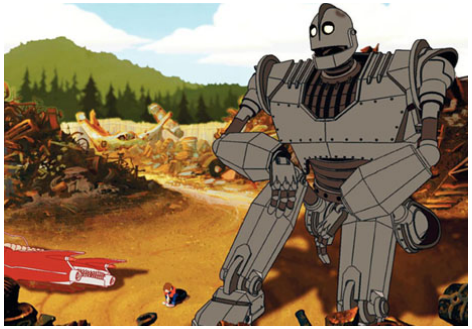
Robots versus Dinosaurs – Who would win?*

?

Tucson IEEE chapter talk December 16, 2008



Unknown Editor, Microwaves101.com

Jack Kouzoujian, Matrix Test Equipment

* This talk is mostly about a new class of power dividers, but who would come to a talk with the boring title “A New Class of Power Dividers?

Why am I the guest speaker?

- Several reasons…
  - Budget for speaker was $0
  - Search for speaker began two weeks ago
  - Brenda volunteered me! Again!

Outline

- N-way equal power splitters – why do we need them?
- N-way splitters – how do we build them?
  - Review of Wilkinson’s idea
  - Planar N-way Wilkinson limitations
- Review of Parad and Moynihan’s unequal 2-way splitter
  - An assumption that has confused engineers for 43 years
  - A new degree of freedom revealed
- Robots versus dinosaurs – who would win?
- Lim and Eom’s unique three-way splitter
- Jack’s idea: use unequal splitter to achieve equal 3-way, 5-way, etc.
  - Three-way examples
    - Based on Parad and Moynihan
    - Applying maximally-flat transformer
  - Five-way example
    - Extra sections facilitate millimeterwave implementations
- Conclusions

N-way power splitters – why do we need them?

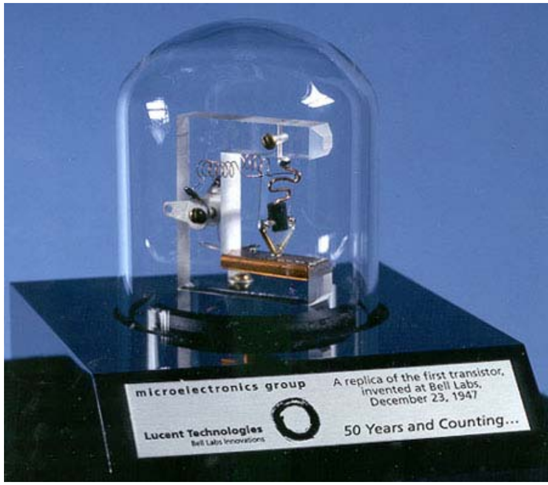
- Since Shockley *et al* invented the transistor in 1947, engineers have tried to replaced tubes for high-power RF/microwave sources
- Early efforts: IMPATT diode
  - Requires hundreds of devices to achieve kW level, with expensive circulators at each element.
  - Can meet efficiency requirements.
  - Raytheon's original AMRAAM missile used IMPATTs, and lost to Hughes (cheaper) traveling wave tube (TWT) based missile
- Later: MESFETs
  - Still requires hundreds of elements, unaffordable
  - Gain/efficiency much lower than tube
- Recently: pseudomorphic GaAs HEMT
  - Fifty elements for 1000 watts
  - Efficiency is approaching tubes
  - You could make an "automotive" microwave oven operate from 12 volts, but far more expensive than converting 12 VDC to 120 VAC
- Now: gallium nitride HEMT
  - Just tens of elements for 1000 watts.
  - The Holy Grail is finally practical!

Whatever happened to Bell Labs?

- In case you weren't watching, the company that invented the transistor is now French!

William Shockley (seated), John Bardeen, and Walter Brattain, 1948.

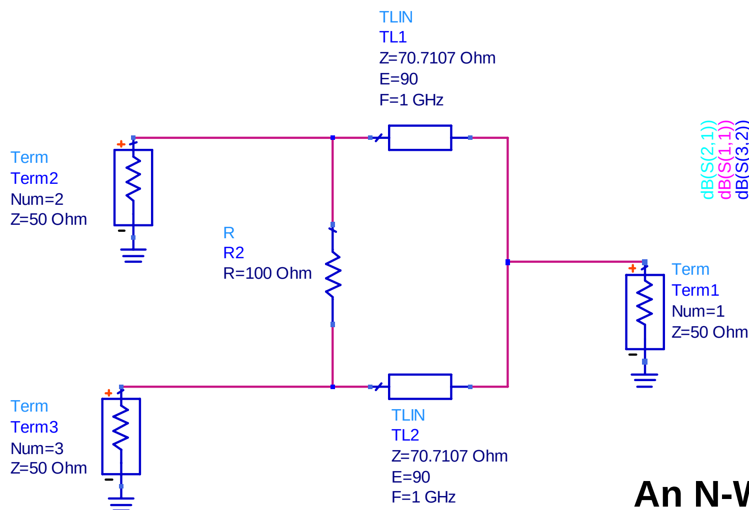
Chicken today, feather pillow tomorrow



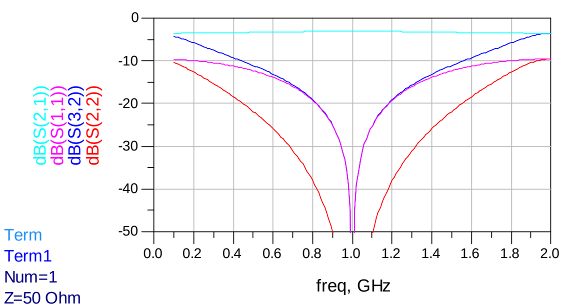
Replica of 1947 transistor

Ernest Wilkinson's ubiquitous splitter

- From basic network theory, you can't build a three-port network that is simultaneously matched and lossless
- Wilkinson added a resistor to isolate the two split ports
  - Three ports are matched, perfect isolation is achieved
  - No effect in "even mode", no effect on combiner efficiency



Simple 2-way Wilkinson



E. J. WILKINSON

An N-Way Hybrid Power Divider
Wilkinson, E.J.;
Microwave Theory and Techniques, IRE Transactions on
Volume 8, Issue 1, January 1960 Page(s):116 - 118

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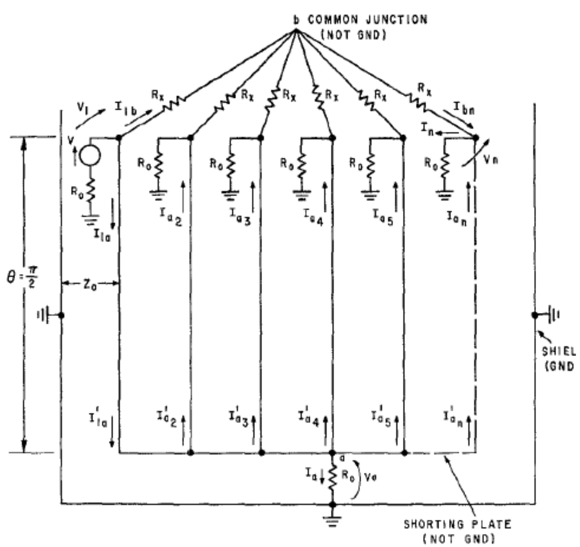
Ernest Wilkinson’s ubiquitous splitter continued

- The original paper was for an N-way splitter
- Requires a “star resistor” to terminate all of the ports
- Can’t make greater than N=2 layout in two dimensions
- Symmetry can be a cruel master!



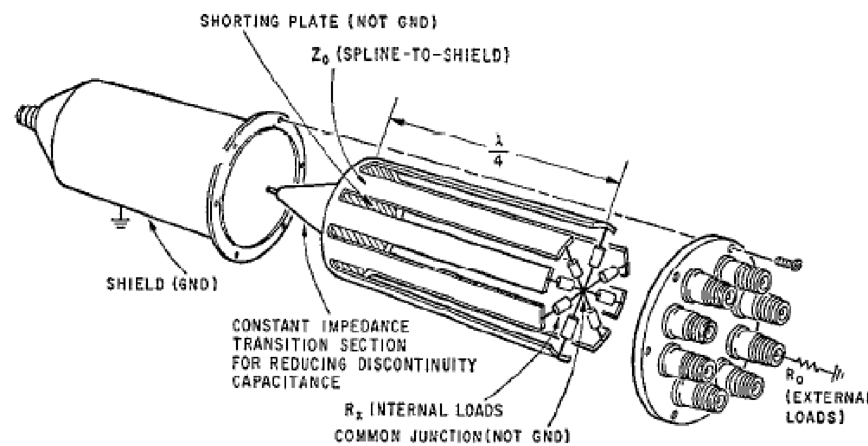


Fig. 2.

Multi-section Wilkinsons

- Cohn's paper shows how to apply transformer theory to design very wideband Wilkinsons with up to seven sections
- Theoretically you can get infinite bandwidth with infinite sections
- In practice, decade bandwidth is achieved
- Calculation of optimum resistors is challenging
  - Luckily, Microwaves101 has a spreadsheet download that does this for you!

Seymour Cohn

A Class of Broadband Three-Port TEM-Mode Hybrids
Cohn, S.B.;
Microwave Theory and Techniques, IEEE Transactions on
Volume 19, Issue 2, Feb 1968 Page(s):110 - 116

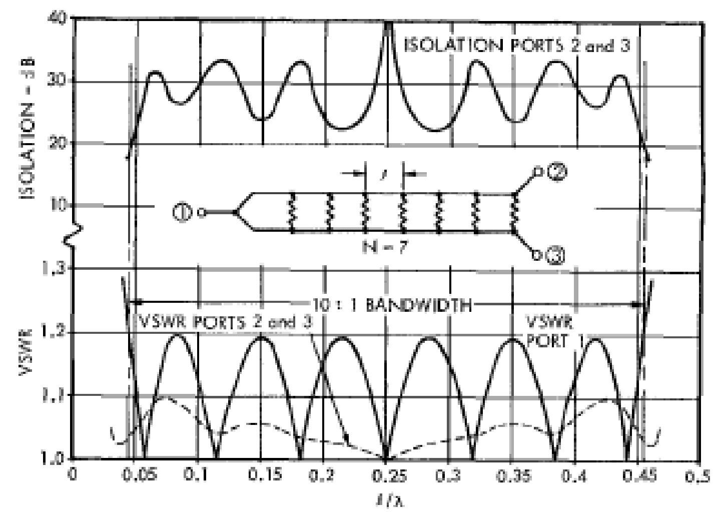
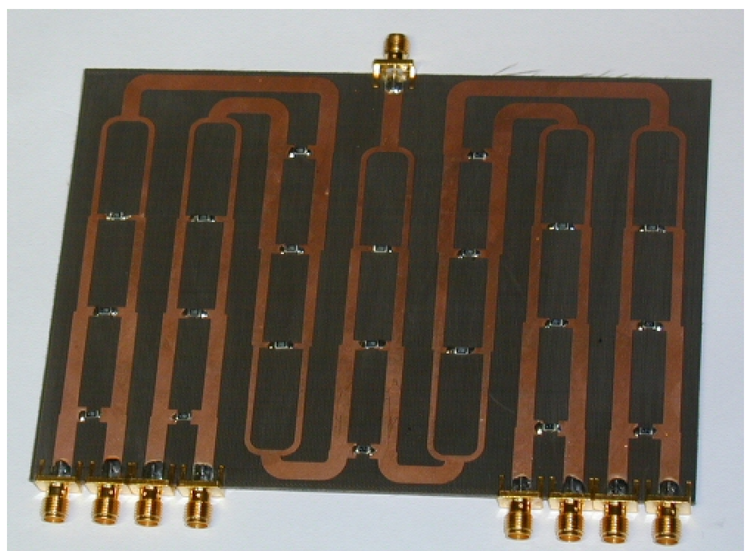


Fig. 8. Response curves, $N=7$, $f_2/f_1=10$.

Corporate Wilkinson structures

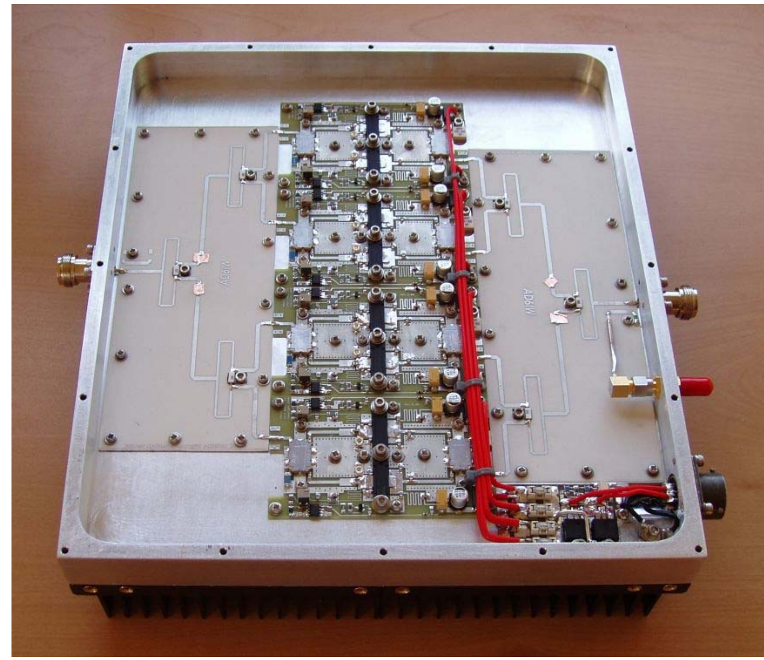
- Corporate structures are used to split/combine very high "N"
- Binary possibilities: 2-way, 4-way, 8-way, 16-way…
- What if all you want is a 3-way or 5-way?



Eight-way, three section equal-split Wilkinson

Why do we need isolation in a power combiner?

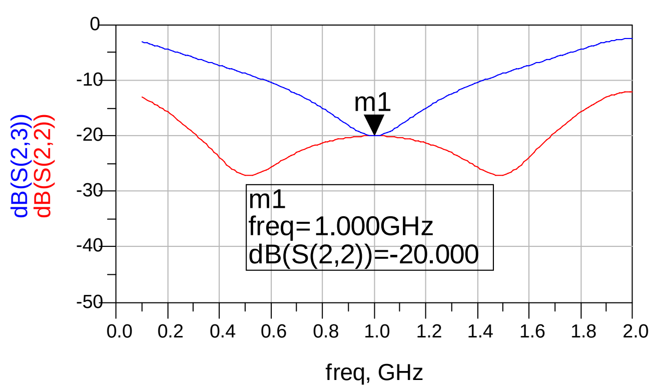
- Two reasons:
  - Isolate active devices to prevent spurious oscillations
  - Graceful degradation
- 20 dB isolation is a good figure of merit (explained on next chart)

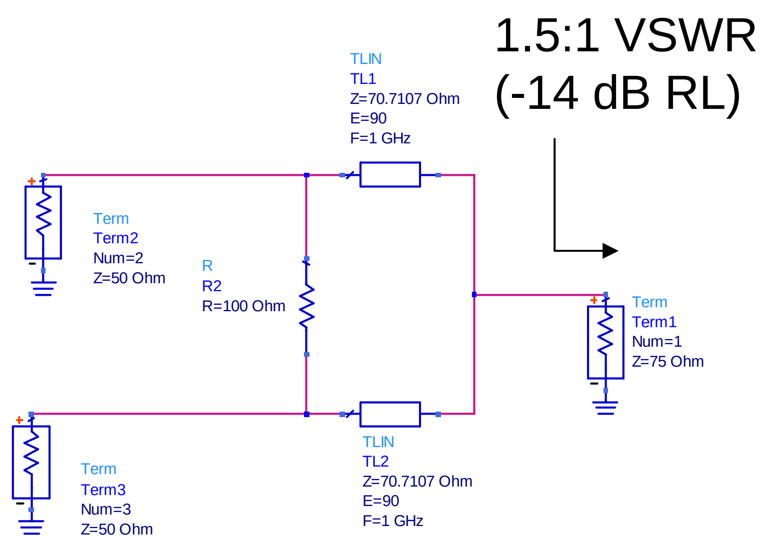


Solid-state power amp using Wilkinson power combiner

Isolation issue with Wilkinson splitters

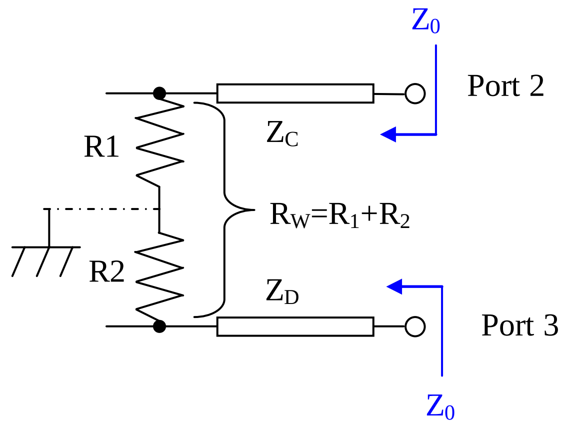
- Rule of thumb: isolation from Port 2 to Port 3 will be no better than 6 dB more than the return loss (in dB) presented to Port 1
- If the solid-state power amplifier sees a 1.5:1 VSWR at the output, isolation between amplifiers will only be 20 dB.
- Bottom line: don’t waste time designing for more than 20 dB isolation, you probably won’t get it!





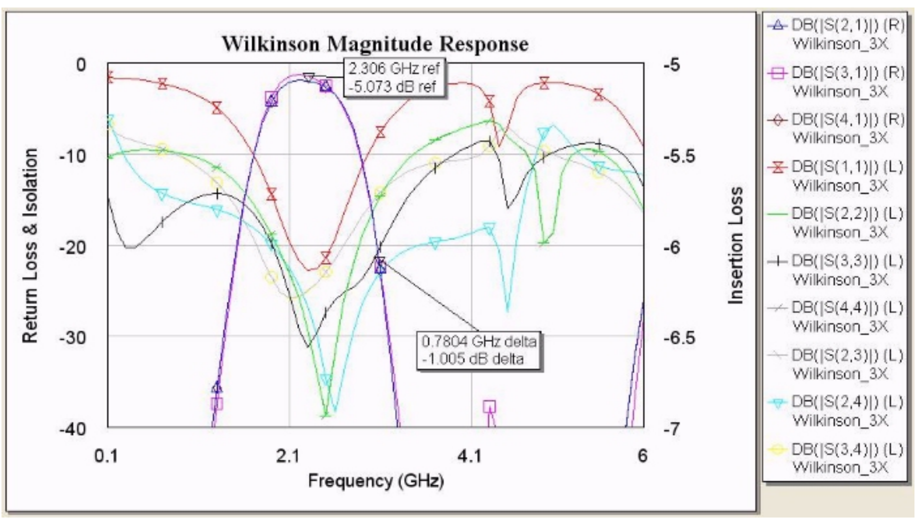
Calculating the “dump” resistors

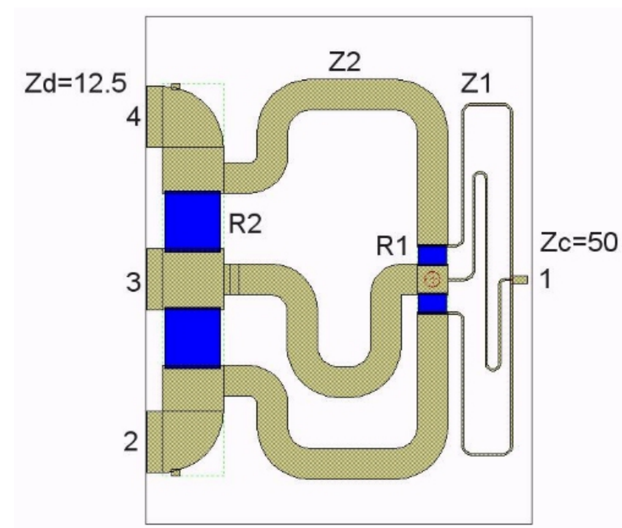
- Cohn showed how to calculate isolation resistors, for multi-section networks using odd mode analysis
  - In odd mode, the common port is at a virtual ground
  - Looking back into the network, need to see Z0 terminations on both split ports.
- For single-section Wilkinsons, calculation is simple.



Planar N-way Wilkinsons

- Over the years, many engineers have resorted to "reduced symmetry" to realize N-way planar Wilkinsons
- The price that is paid is reduced isolation, amplitude/phase imbalance, and reduced bandwidth





Symmetry is a cruel master!

Wilkinson and Cohn are Hall of Famers!

- Microwaves101 Hall of Fame candidates must have made at least one truly great contribution to microwave engineering.
  - List starts with Napier – inventor of logarithms!
  - Currently ends with Herb Kroemer, inventor of the HBT
  - Faraday, Maxwell, Hertz, Lange, Wilkinson, and many others are in between
- Not a day goes by when the name "Wilkinson" is not used in the microwave industry
- Cohn wrote a ton of IEEE papers that are as relevant today as when he wrote them 50+ years ago

Unequal-split Wilkinson reference

- 1965 IEEE paper by Sylvania engineers Lenny Parad and Robert Moynihan "Split Tee Power Divider"
  - Not sure why they didn't use Wilkinson's name in the title
  - This paper seems to be the universal reference for unequal-split Wilkinsons

Lenny Parad

Robert Moynihan

Split-Tee Power Divider
Parad, L.I.; Moynihan, R.L.;
Microwave Theory and Techniques, IEEE Transactions on
Volume 13, Issue 1, Jan 1965 Page(s):91 - 95

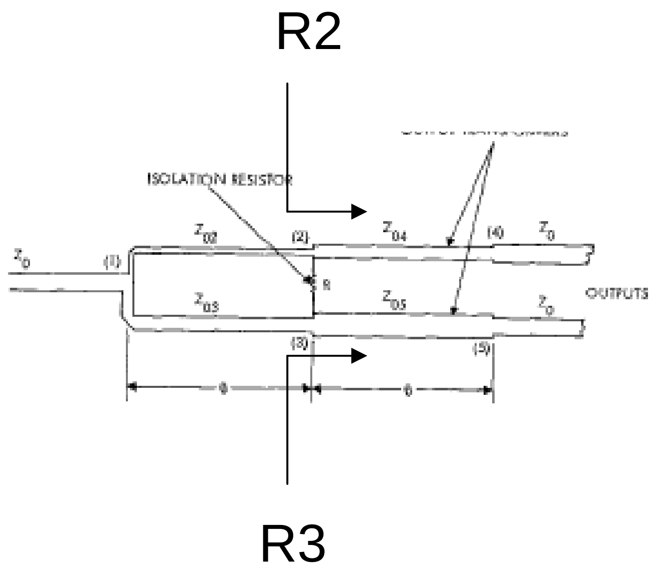
A critical assumption…

- Parad and Moynihan made an assumption in developing design equations
- Using their assumption, all four impedances are uniquely calculated from power split ratio
- *<u>They never said this was the only solution!</u>*

$$\frac{\text{POWER AT PORT 4}}{\text{POWER AT PORT 5}} = \frac{1}{K^2} \qquad Z_{02} = Z_0\sqrt{K(1+K^2)} \qquad Z_{04} = Z_0\sqrt{K}$$

$$\text{CENTER FREQUENCY AT } \theta = 90^\circ \qquad Z_{03} = Z_0\sqrt{\frac{1+K^2}{K^3}} \qquad Z_{05} = \frac{Z_0}{\sqrt{K}}$$

$$R = Z_0\frac{1+K^2}{K}$$



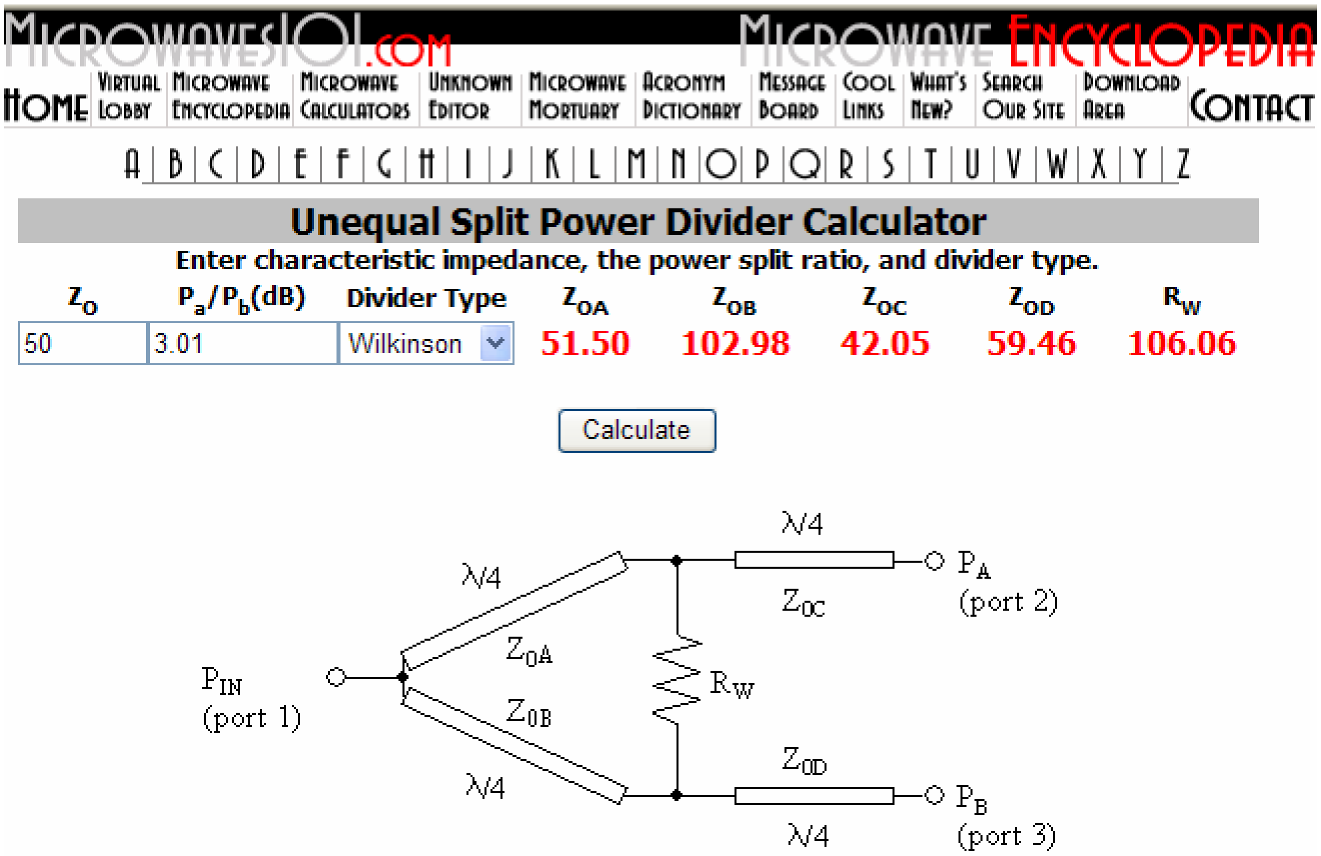
The output impedances R_2 and R_3 are chosen to be

$$R_2 = KZ_o \qquad R_3 = \frac{Z_o}{K} \qquad (2)$$

As will be shown, this choice causes the output transformers to have identical phase-transfer characteristics.

The assumption

Microwaves101 unequal-split power divider on-line calculator is based on Parad and Moynihan



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Recent published work on 4:1 power splitter

- Uses equations from Parad and Moynihan (but authors referenced Pozar's *Microwave Engineering*)
- Defected ground structure used to realize 158 ohm transmission line extracted from Parad and Moynihan's equations
- Authors could have used our analysis to reduce required high impedance. And skipped the fancy DGS!
  - Caveat: bandwidth would be reduced

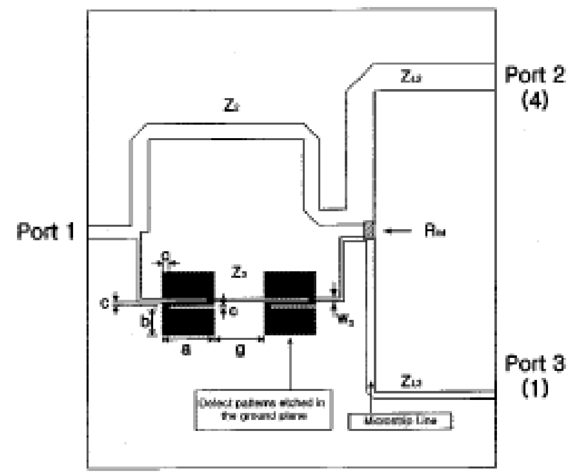


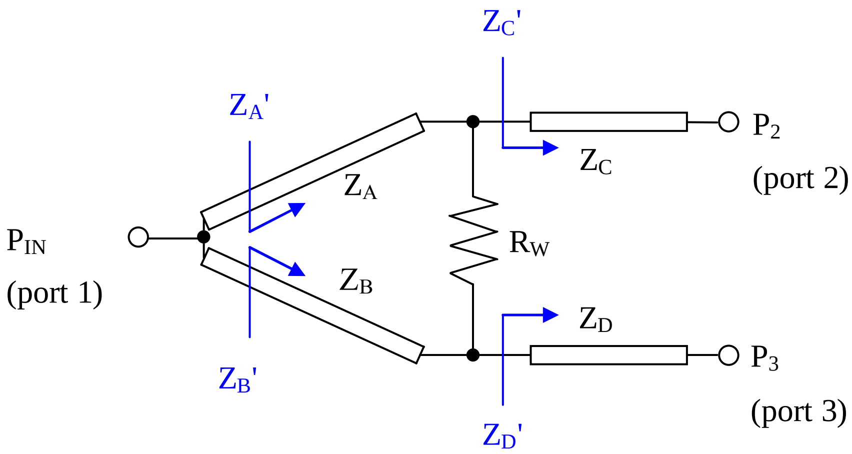
Fig. 2. The proposed 4 : 1 unequal Wilkinson power divider which has a 158 Ω microstrip line with the DGS. The two identical DGS patterns are etched in the bottom plane, i.e., the ground plane. The DGS dimensions are $a = b = g = 6$ mm and $c = 0.4$ mm. Z_{L2} and Z_{L3} are the $\lambda/4$ transformers between R_2, R_3, and Z_0.

Z0	Pick ZA	Pick P3/P2	ZB	ZC	ZD
50	20	0.25	80.00	17.89	35.78
50	**39.5**	0.25	158.00	35.33	70.66

A 4:1 unequal Wilkinson power divider
Jeng-Sik Lim; Sung-Won Lee; Chul-Soo Kim; Jun-Seek Park; Dal Ahn; Sangwook Nam;
Microwave and Wireless Components Letters, IEEE
Volume 11, Issue 3, March 2001 Page(s):124 - 126

New look at the problem

- There are just three RF criteria that must be met:
- ZA′ in parallel with ZB′ must equal Z0 for impedance match
- Because the voltage at the input node is the same looking into each arm. power split is proportional to RF current split, and will be inversely proportional to ratio of impedances ZA′/ZB′
- Voltage across isolation resistor has to be zero, when power is applied from common port. In order for this to happen, the impedance ratio ZA′/ZB′ must be maintained through first legs of the splitter.



$$Z_0 = \frac{Z_A' \cdot Z_B'}{Z_A' + Z_B'}$$

$$Z_C' = \sqrt{P_3/P_2} \cdot Z_0$$

$$Z_D' = \frac{Z_0}{\sqrt{P_3/P_2}}$$

There's a better explanation at Microwaves101.com!

The solution

- Let Z_A be an independent variable and solve for the other three impedances
- Dump resistor solved by to terminate odd mode

Line impedances

$$Z_B = \frac{Z_A}{P_3/P_2}$$

$$Z_C = \frac{Z_A}{\sqrt{1+P_3/P_2}}$$

$$Z_D = Z_B \cdot \sqrt{\frac{P_3/P_2}{(1+P_3/P_2)}} = \frac{Z_A}{\sqrt{P_3/P_2}\sqrt{1+P_3/P_2}}$$

Dump resistor

$$R_1 = \frac{Z_C{}^2}{Z_0} = \frac{Z_A{}^2}{Z_0(1+P_3/P_2)}$$

$$R_2 = \frac{Z_D{}^2}{Z_0} = \frac{Z_A{}^2}{Z_0(1+P_3/P_2)P_3/P_2}$$

$$R_W = R_1 + R_2 = \frac{Z_A{}^2}{Z_0\,P_3/P_2}$$

Save time: look for free Excel spreadsheet download on Microwaves101.com

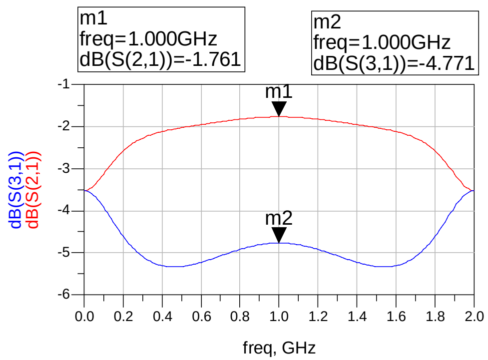
Now you have a choice!

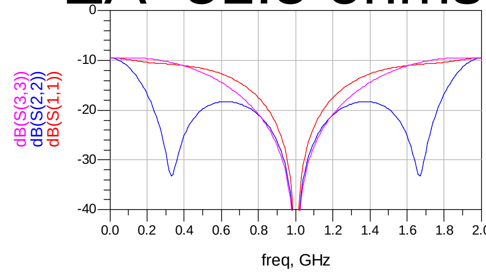
- Split ratio 2:1 (67%/33%)
  - ZA=51.1 ohms is Parad and Moynihan's result
  - ZA=59.46 ohms represents max flat transformation (more about that later)
  - ZA=40 ohms makes other line impedances easier to achieve
    - Highest impedance (ZB) is 80 ohms, Parad and Moynihan would require 103 ohms

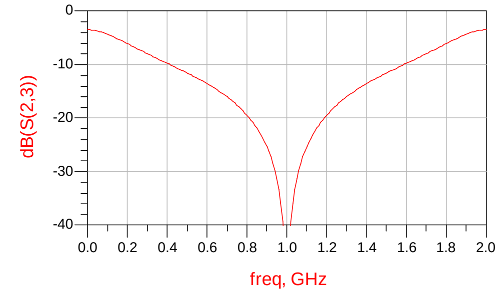
Z0	Pick ZA	Pick P3/P2	ZB	ZC	ZD
50	40	0.5	80.00	32.66	46.19
50	**51.5**	0.5	103.00	42.05	59.47
50	**59.46**	0.5	118.92	48.55	68.66

Comparison of RF performance

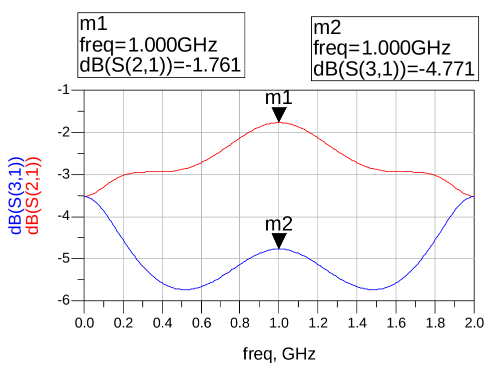
ZA=51.5 ohms

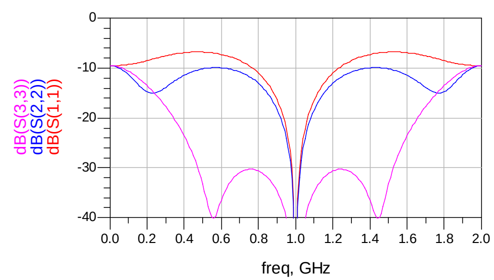


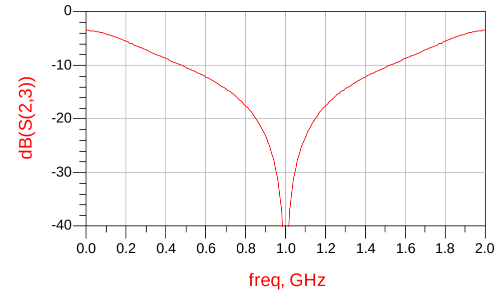




ZA=40 ohms



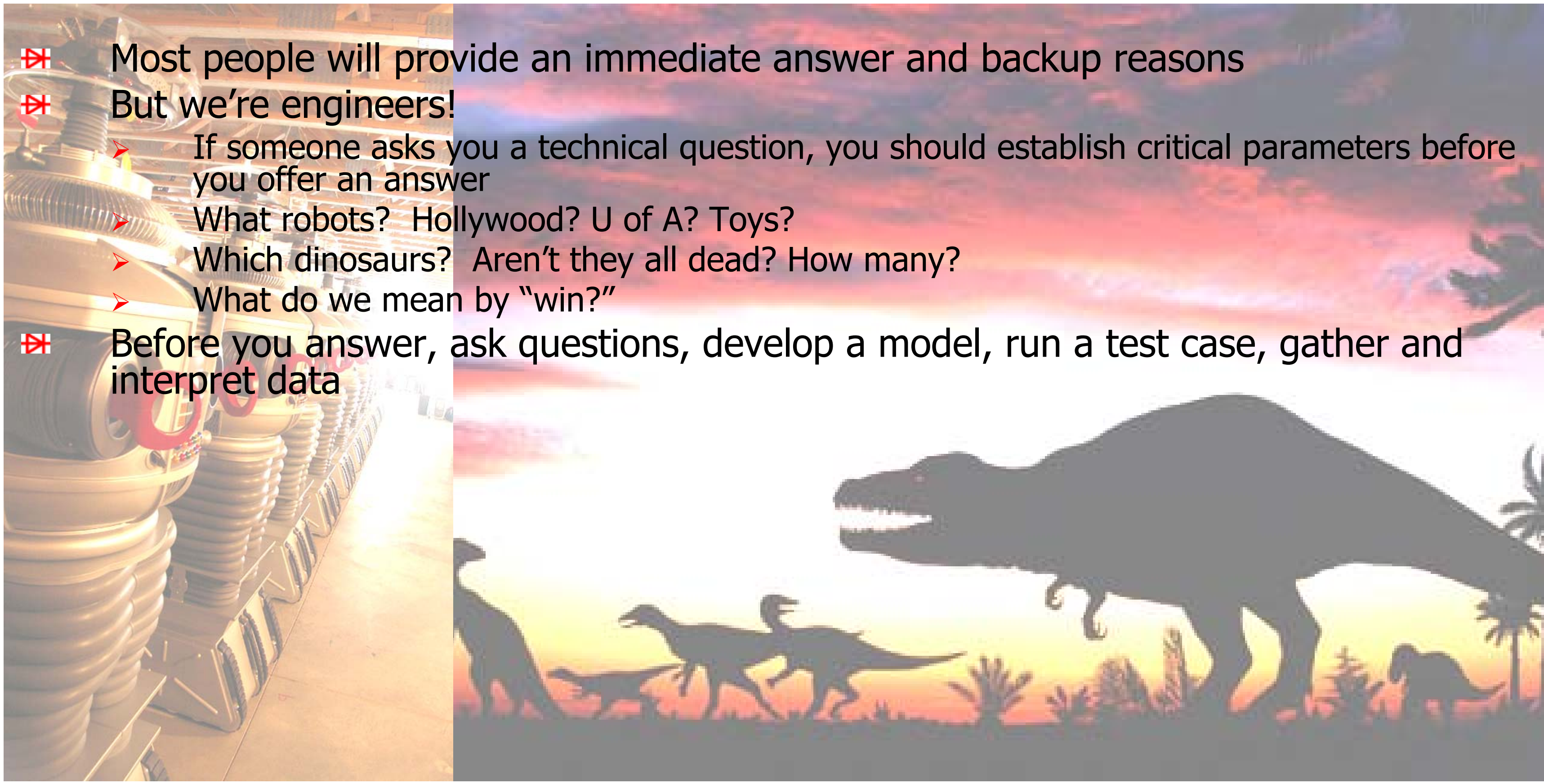




Z_A=40 ohms has narrower bandwidth, but it might be easier to manufacture. At least we now have that tradeoff!

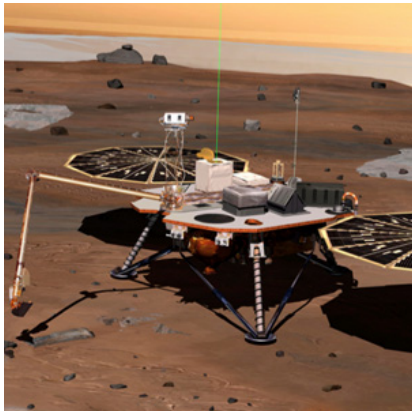
Robots versus Dinosaurs?

- Most people will provide an immediate answer and backup reasons
- But we're engineers!
  - If someone asks you a technical question, you should establish critical parameters before you offer an answer
  - What robots? Hollywood? U of A? Toys?
  - Which dinosaurs? Aren't they all dead? How many?
  - What do we mean by "win?"
- Before you answer, ask questions, develop a model, run a test case, gather and interpret data



Robots versus Dinosaurs – possible data point?

- Here at U of A, there are certainly some robots we could use…
  - Could we borrow one for a little demonstration?
- What's the closest thing we have to a dinosaur in Tucson? Perhaps a Gila monster?
- How can we get them to fight? Tape a ham sandwich to the robot?



Robots easily win Google search

- Robot images found by Google: 16,000,000
- Dinosaurs: 1,600,000

Apartment for rent!

- On North Park, front unit of duplex
  - 1.6 miles from where you are sitting!
- 900 square feet 2BR 1BA
- Entirely new kitchen!
  - Gas stove
  - Washer and drier included
  - Polished concrete floor
- Gas heat, evap cooling
- Large fenced/shaded yard
- $800/month/all utilities included
- Available January 15, 2009
- Contact Principalpropertymanagement.com if interested

Trust me, this is relevant!

Robots versus Dinosaurs – Ground Zero

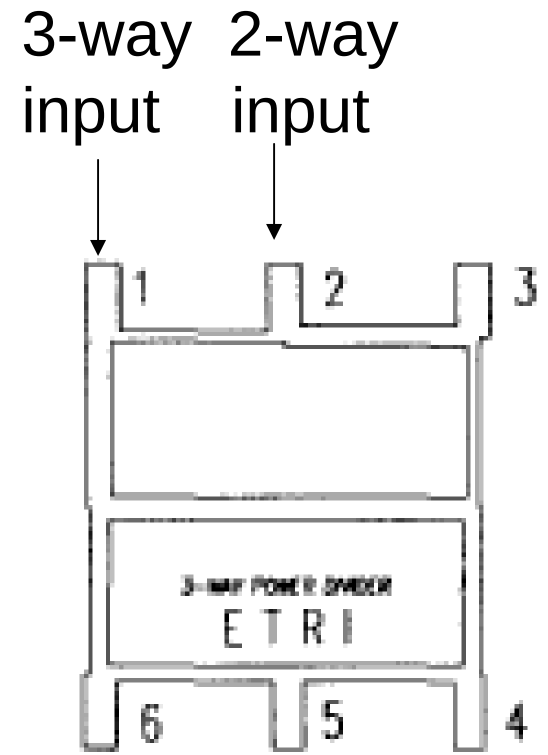
- Inspiration for title of this talk came from neighbor on Park Street
  - U of A sophomore “Nick”
- Beer pong table in garage, labeled “robots” on one side, “dinosaurs” on the other
- Not sure which team is winning, sometimes a third team “cops” shuts down the game

For rent

Robots versus Dinosaurs decided here

How to create a planar three-way power combiner?

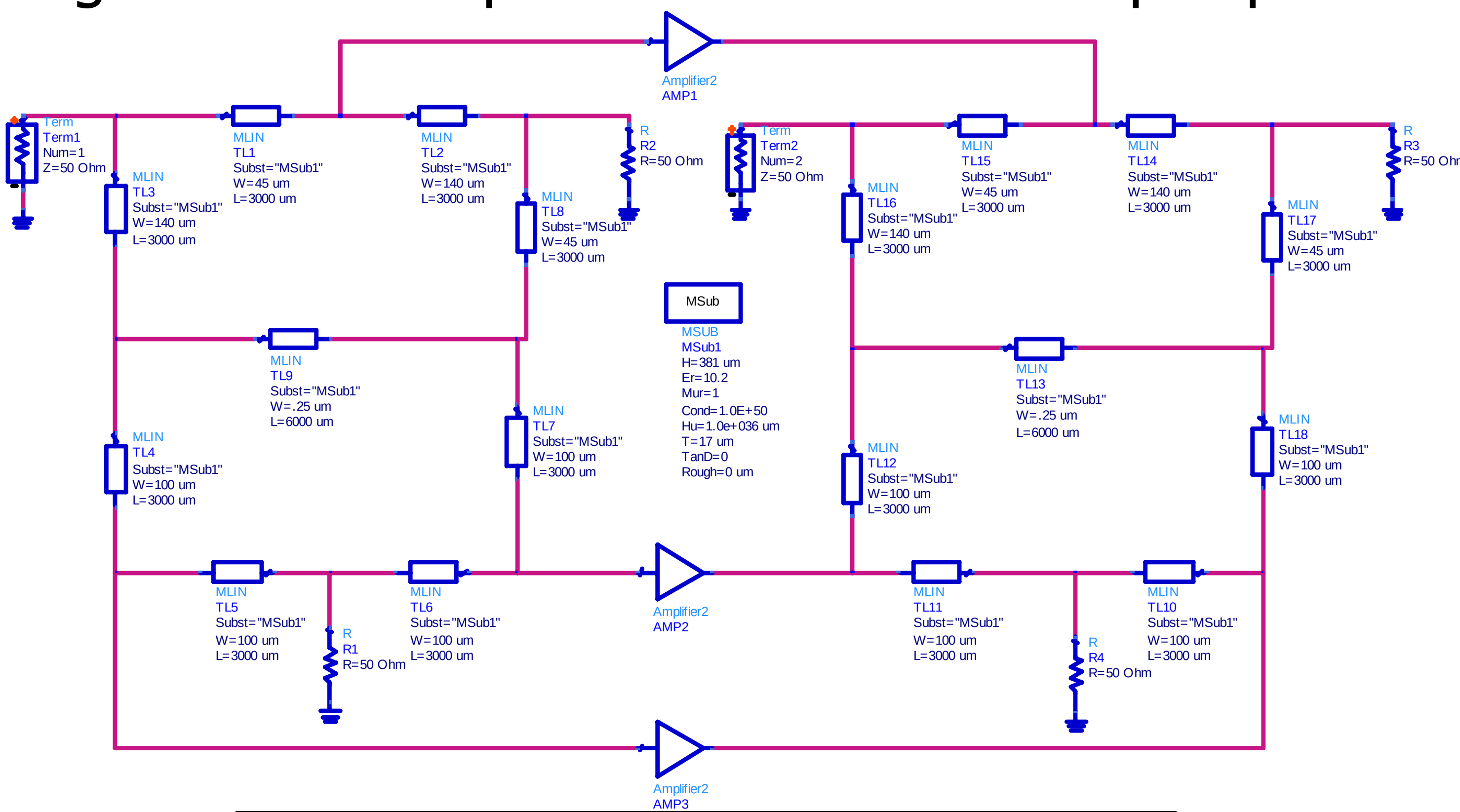
- Someone asked our web site about using the Lim Eom splitter to combine three amplifiers
- Lim Eom is a six-port network that can split two-way or three-way depending on which port is excited
- Remaining (isolated) ports must be terminated



A new 3-way power divider with various output power ratios
Jong-Sik Lim; Soon-Young Eom;
Microwave Symposium Digest, 1996., IEEE MTT-S International
Volume 2, 17-21 June 1996 Page(s):785 - 788 vol.2

There is no practical way to use Lim/Eom for a three-way combiner

- Planar layout will be extremely ugly, because path lengths to the amplifiers have to be of equal phase

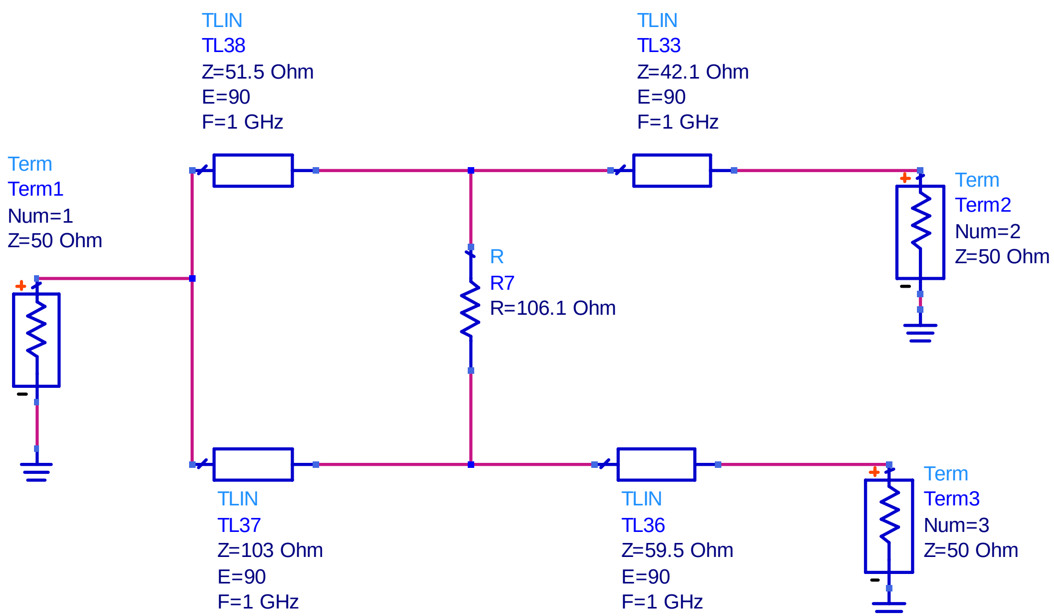


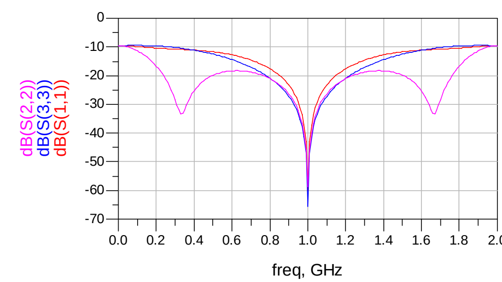
Jack's idea

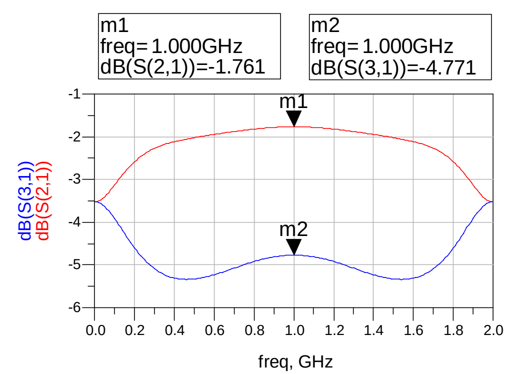
- Create a planar, equal three-way split using an unequal 67%/33% splitter, then split the 67% port into two signals.
- This may not be novel, but Jack and I have developed the technique beyond what you can find in IEEE literature
- We won't fully cover the topic tonight, but if you are interested visit Microwaves101.com and look up "Kouzoujian splitter", or just Google it
  - Check back in a few months, we aren't done!

Start with a 67%/33% unequal splitter

- Note: this example uses the values that Parad and Moynihan would be proud of!

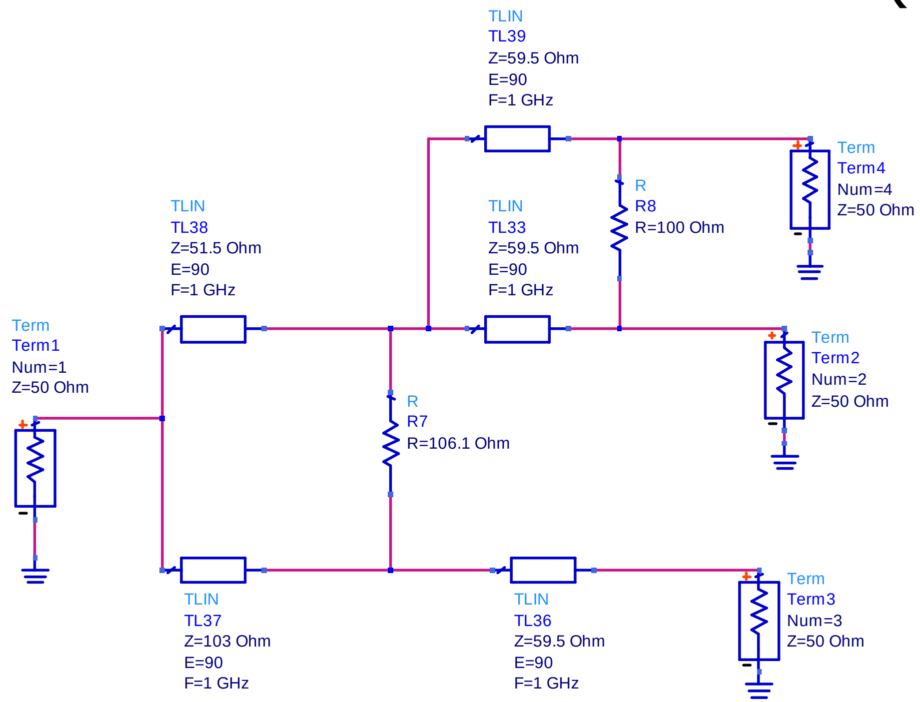


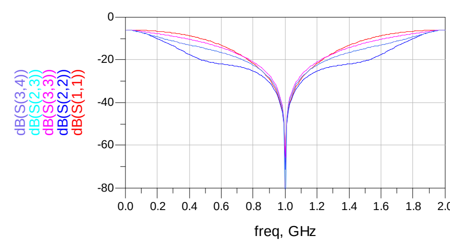


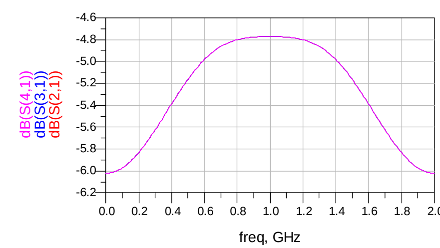


Add a second stage, by splitting the low-impedance arm and adding a second isolation resistor

- Perfect three-way amplitude (and phase) balance and infinite isolation at band center (ideally) are achieved



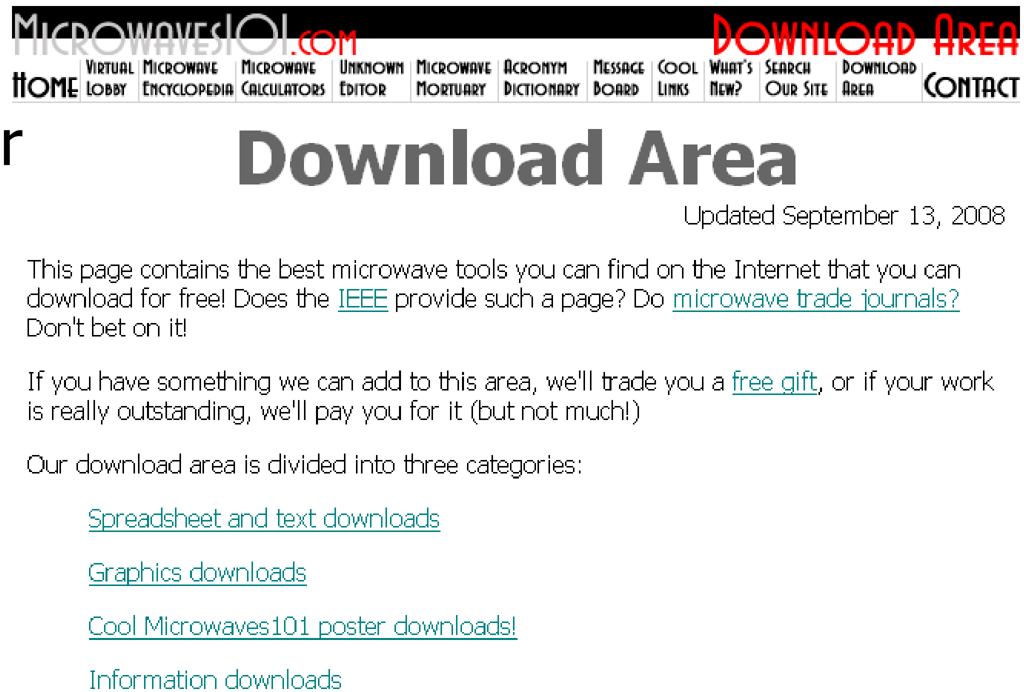




All arms receive -4.77 dB referenced to input

Next: re-examine the problem as a transformer

- Save yourself a week's worth of time, download our transformer spreadsheet courtesy of "The Professor"
- It will synthesize maximally-flat, Chebychev and exponential multi-section transformers



Max-flat transformers

- Math was developed by IRE authors Riblett, Cohn and Collin in the 1950s
- Exact math behind the max-flat transformer is difficult
  - Most engineers use a lookup table using data from Matthai, Young and Jones "Black Bible"
  - So does our downloadable spreadsheet!

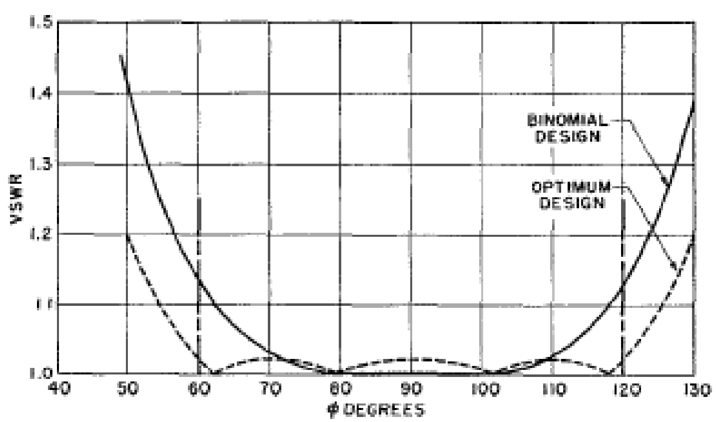


Fig. 2—Theoretical vswr response of a five-step transformer for a total characteristic impedance change of 8:1.

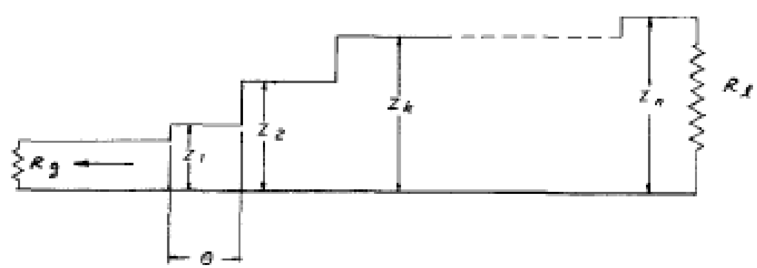
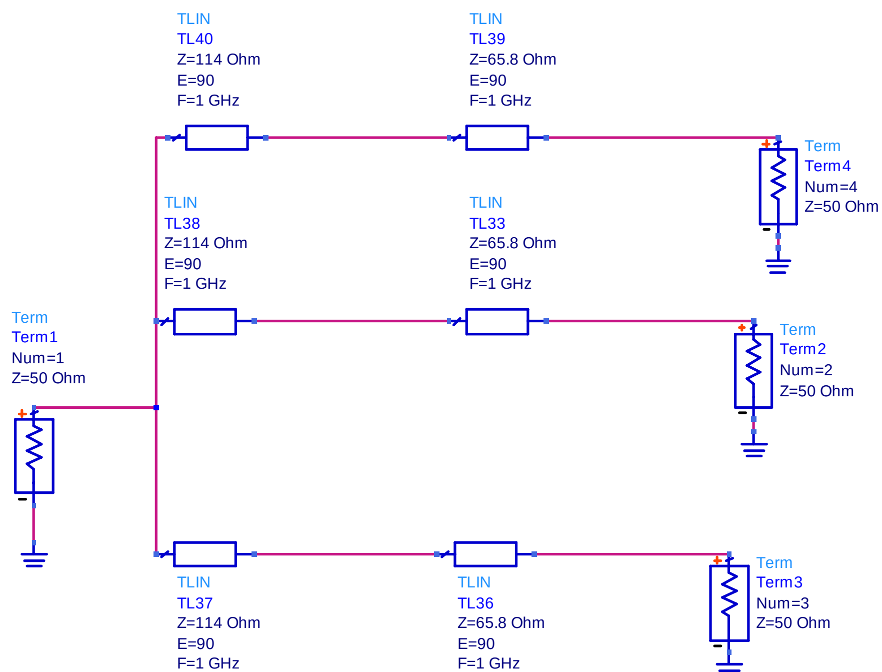


Fig. 1—Schematic of n section transformer.

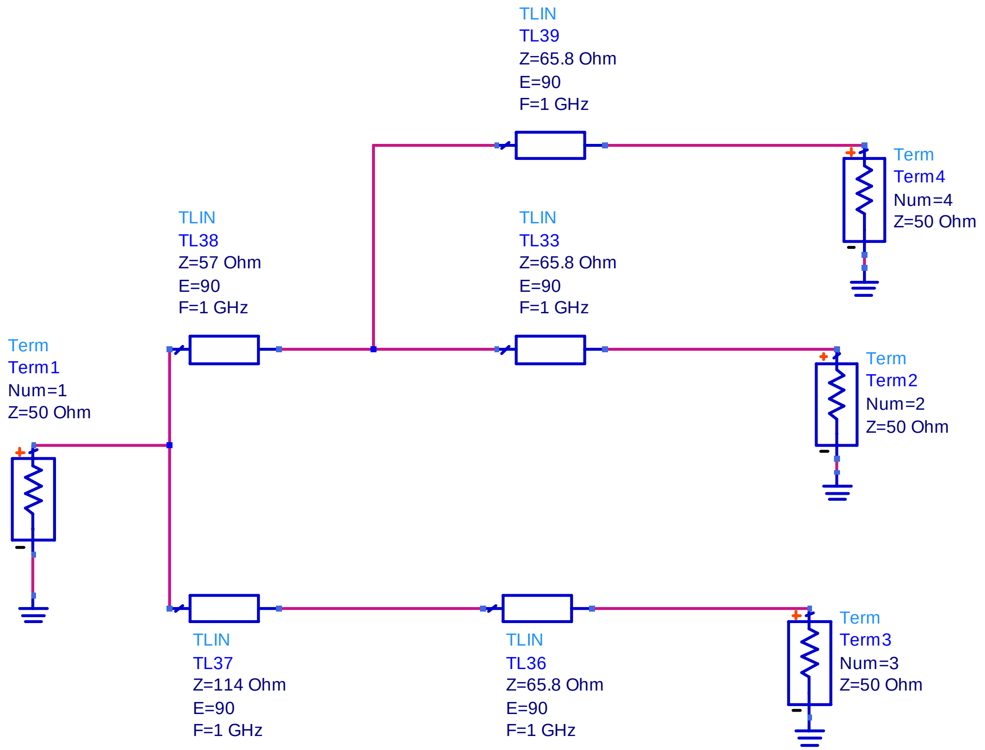
Design procedure is quite simple…

- For three-way split, you need to transform three 50-ohm loads to 150 ohms, so they combine back to fifty ohms in parallel with each other
- Max flat two-step transformation: 114 ohms, then 65.8 ohms
- Max flat provides better end results than Chebychev, but don’t take our word for it, try both!

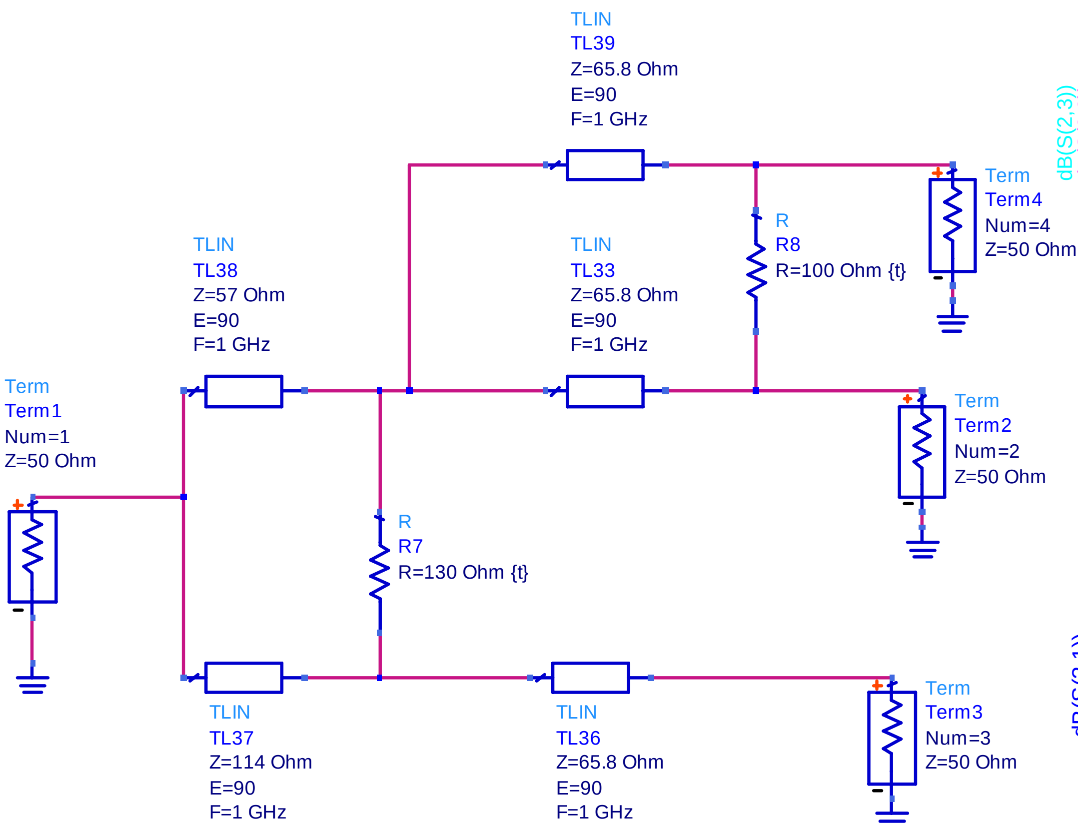


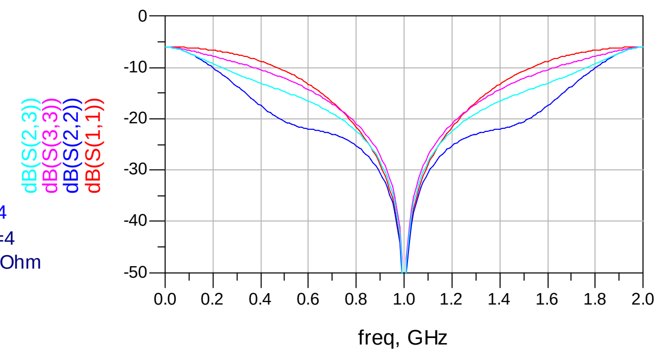
Next, combine two arms

- Combining two arms in parallel requires halving their impedance
  - Two 114 ohm lines become single 57 ohm line
  - Input still sees maximally-flat impedance match

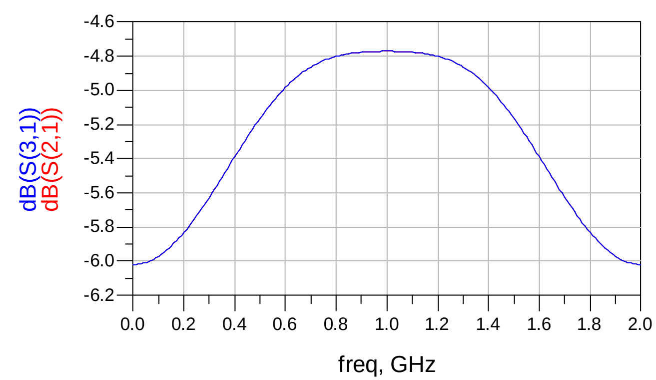


Finally, add isolation resistors



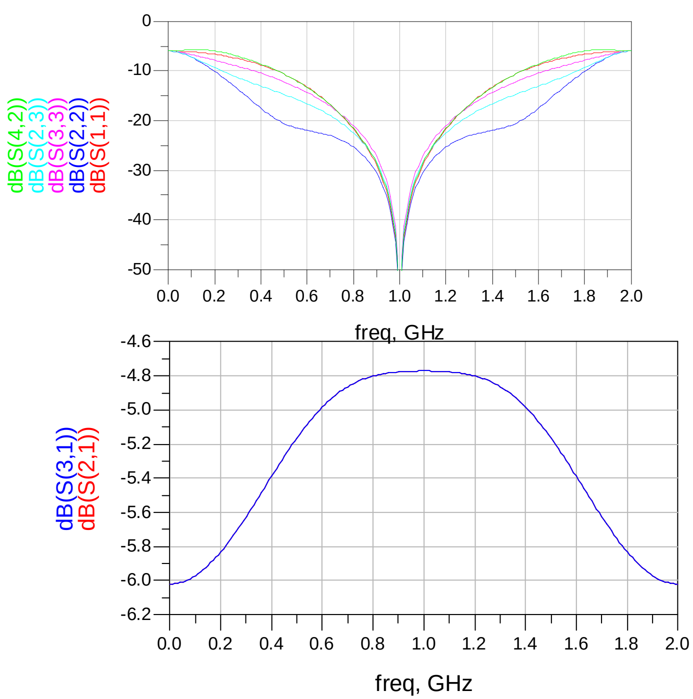


Ideal response is perfect!

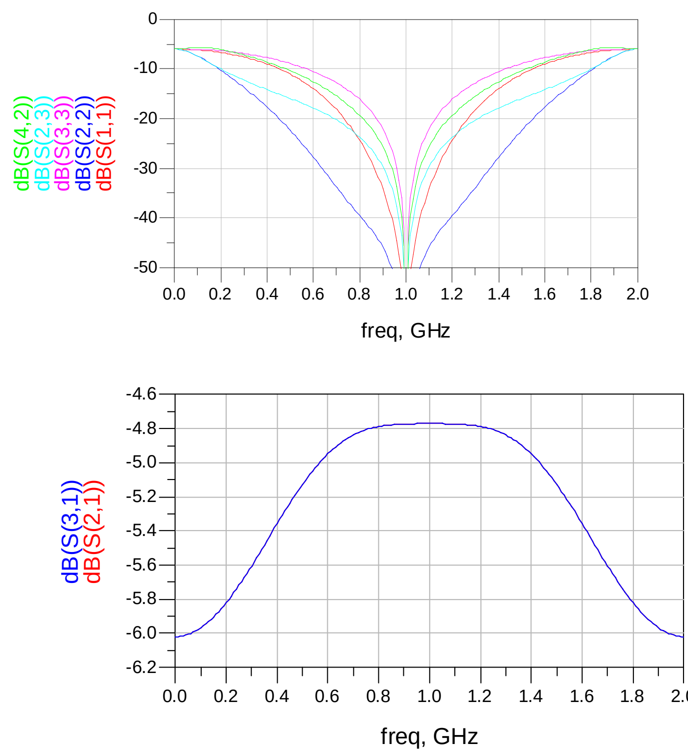


Parad and Moynihan versus max-flat Kouzoujian three-way splitters

- Similar ideal performance, with a degree of freedom



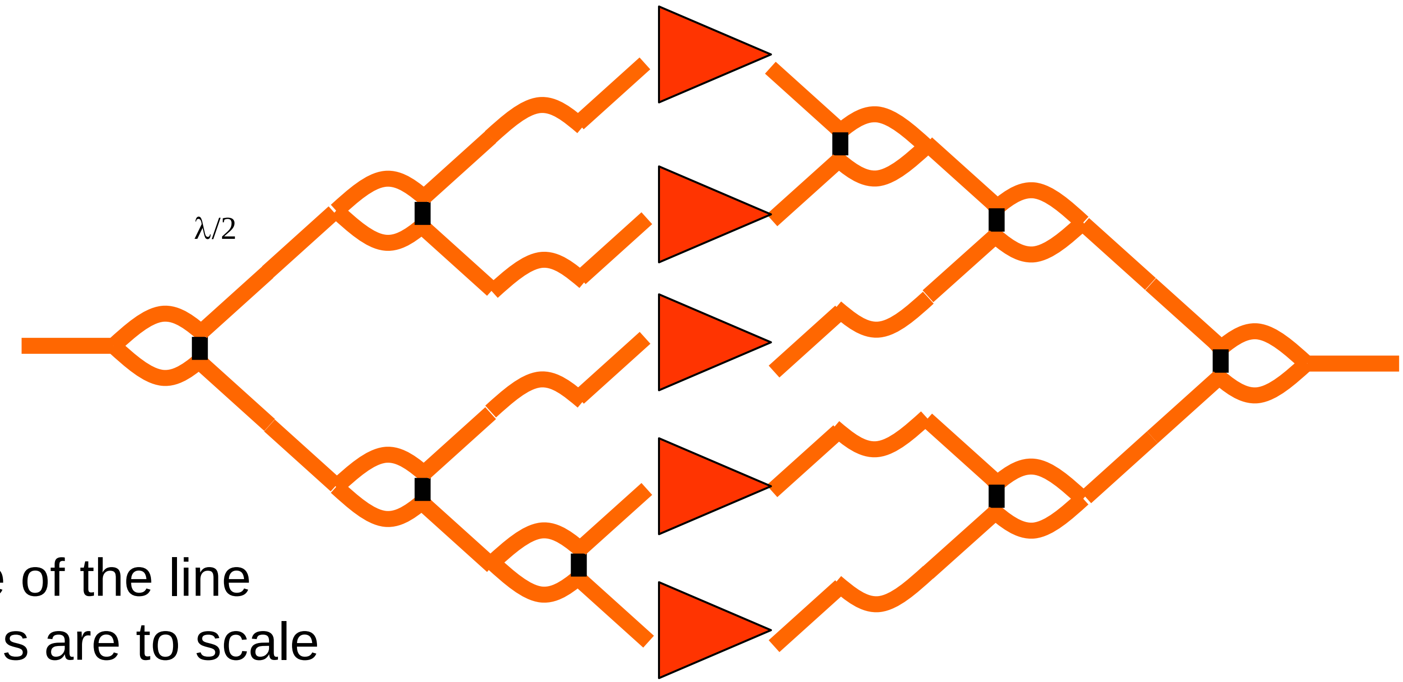
P&M (ZA=51.5 ohms)



Max flat (ZA=59.46 ohms)

Second example: five-way splitter, with “extra” sections

- For power amps that are large compared to a quarter-wavelength, extra sections are needed to facilitate the layout
- This technique will work well for millimeter-wave SSPAs



None of the line widths are to scale

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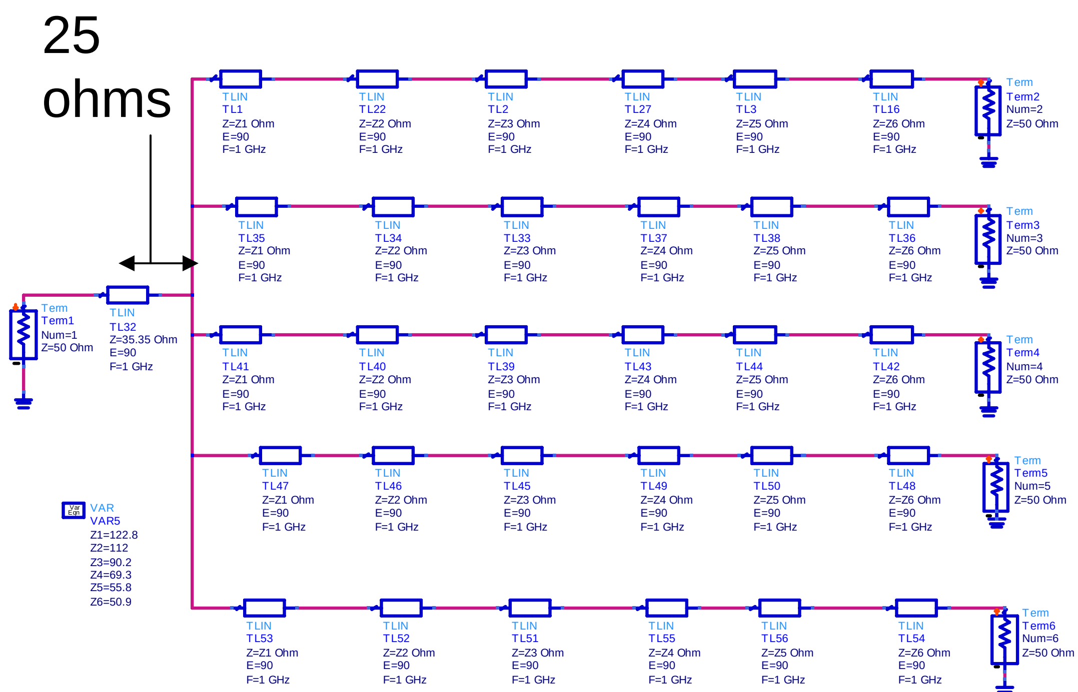
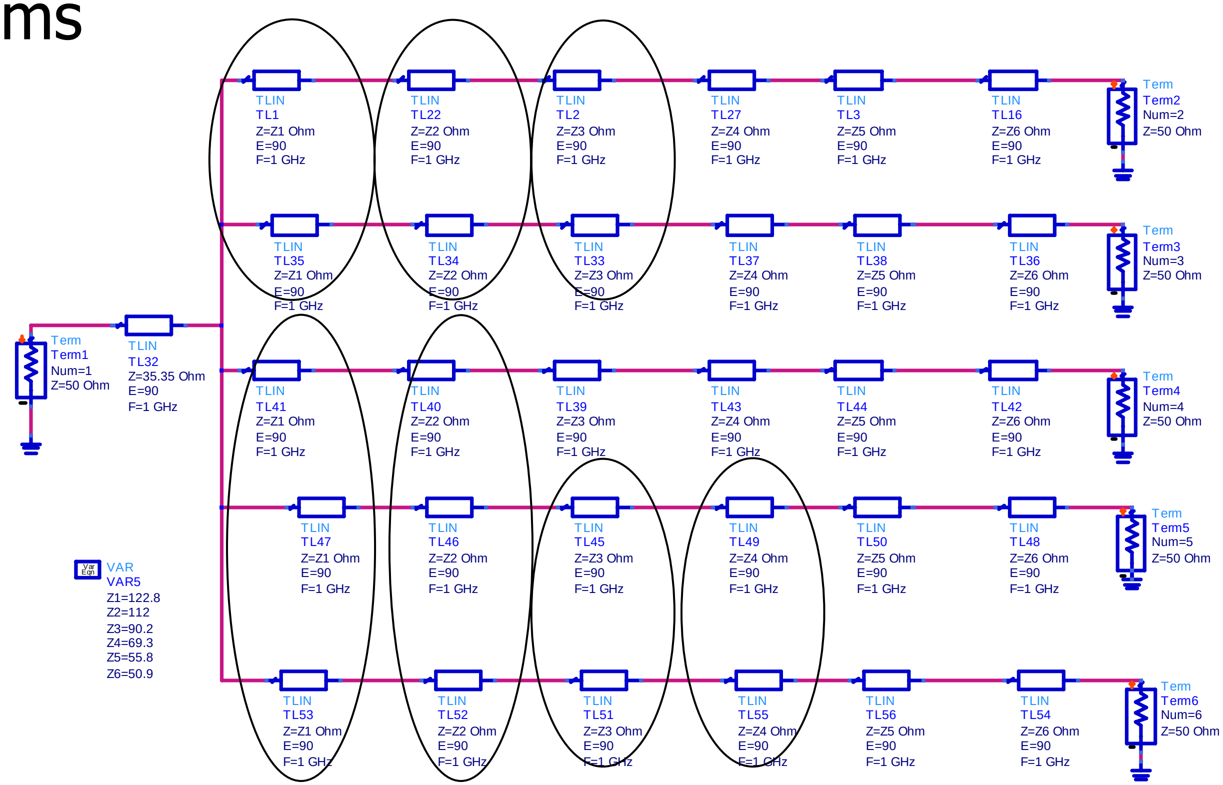
Start with five max-flat six-section impedance transformers

- Transforming 50 ohms to 250 ohms is not practical because you can't achieve required high impedances in practice
- We made the problem easier by adding a transformation at the common node to bring 50 ohms to 25 ohms



Combine these arms

- Line impedances are divided by number of combined arms



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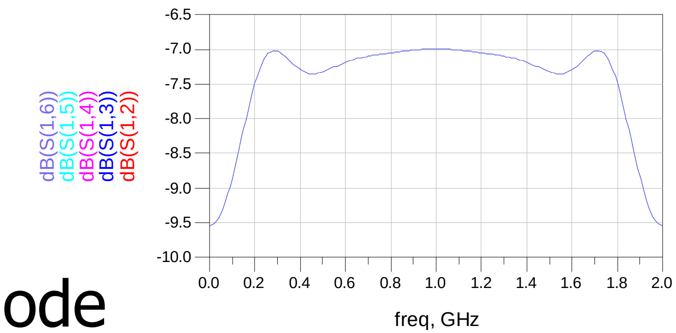
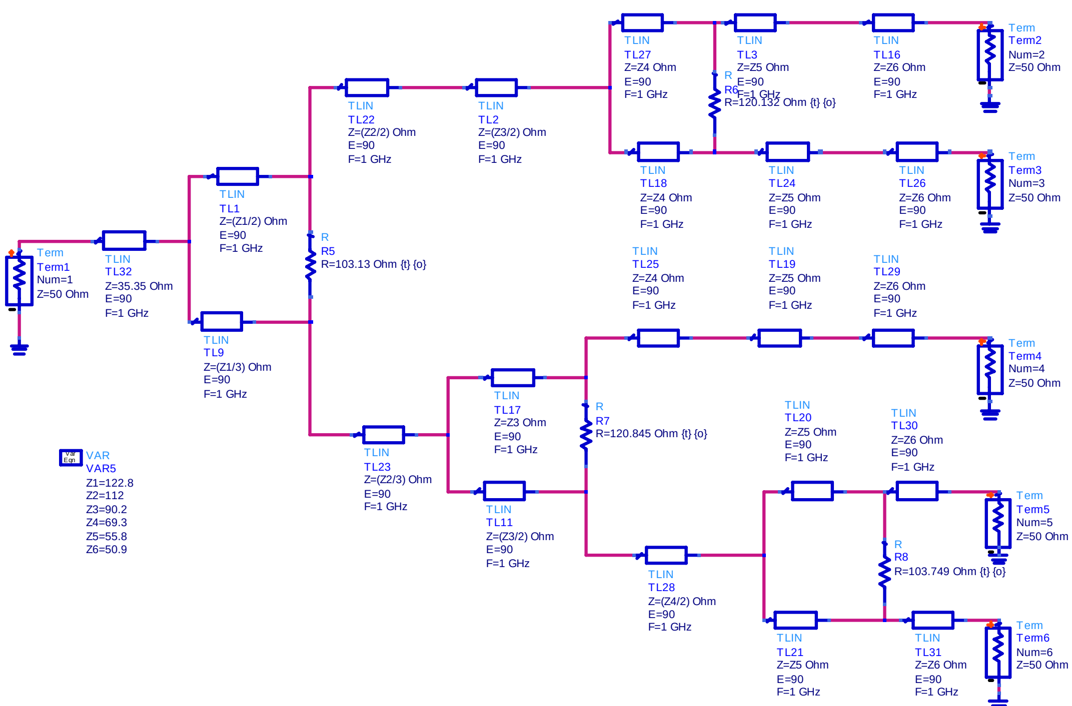
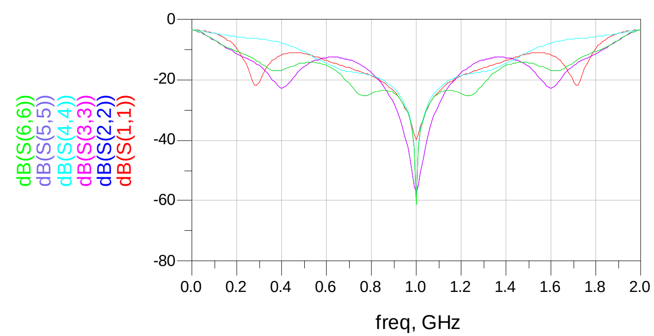
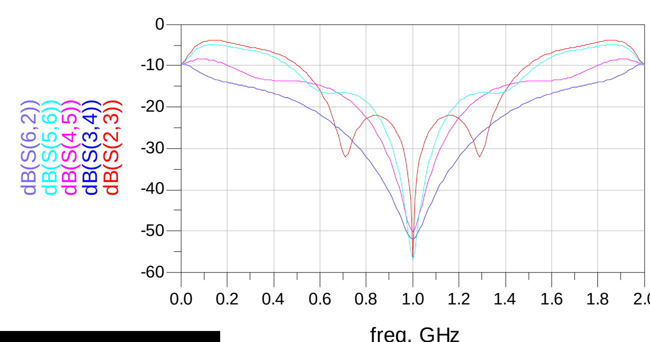
Add isolation resistors to complete the design

- Calculated to terminate the odd mode







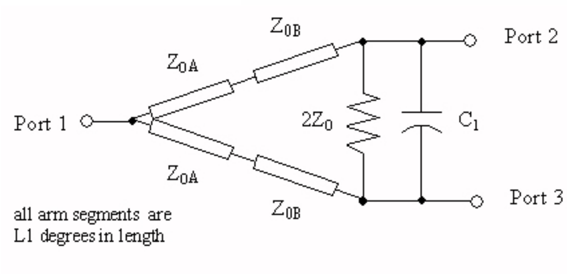


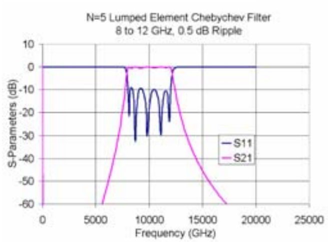
Why didn't we write an IEEE article on this topic?

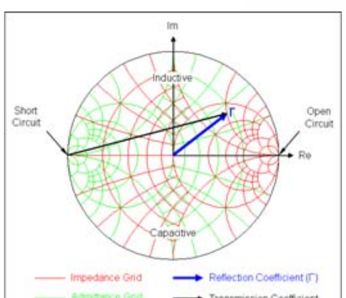
- Microwaves101 is where we "published" this information
- Compared to IEEE journals…
  - No membership fee required to read it
  - No need to wait for peer review
  - Either way, we don't get paid!
- IEEE authors: feel free to reference our work!

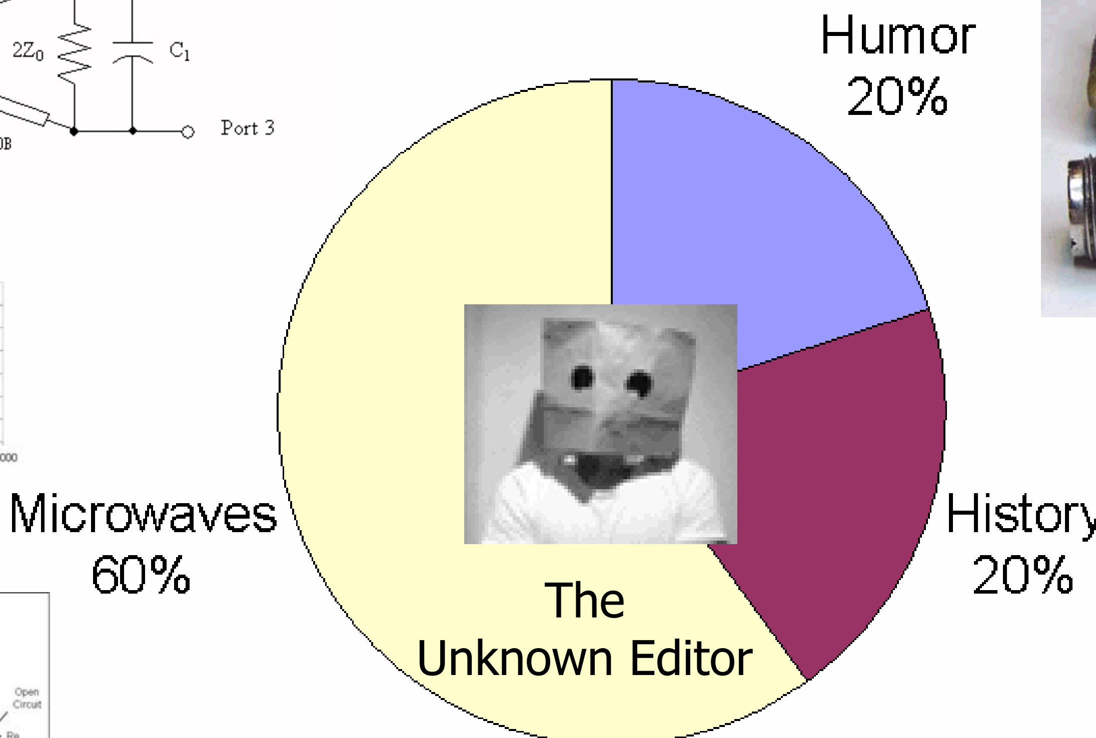
The internet has forever changed what it means to "publish"

Microwaves101 provides a mixture of content









Conclusions

- When someone asks your quick opinion, get further information before you offer an answer
  - Act like an engineer!
- Just because Parad and Moynihan "chose stegosaurus", doesn't mean you shouldn't look at other dinosaurs
  - We recovered an independent variable for unequal-split Wilkinsons
- Planar N-way Wilkinsons suffer from poor isolation and imbalance
  - Symmetry is a cruel master!
- We introduced a new type of N-way power splitter that can provide "odd" splits like N=3 and N=5
  - Perfect isolation is achieved in a compact planar layout

- January 2009 issue of *Microwaves and RF* contains an in-depth interview with the Unknown Editor!

Thanks for staying awake if you managed to!