Transmission Line Filters Beyond Stubs and Traps

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ARRL Pacificon Presentations by K6OIK

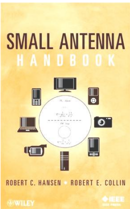
Archived at
http://www.fars.k6ya.org

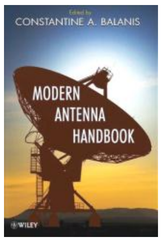
1999	Mysteries of the Smith Chart	
2000	Jam-Resistant Repeater Technology: Signal Separation, Identification, Routing, Control, and Automatic Logging	
2001	Mysteries of the Smith Chart	✓
2002	How-to-Make Better RFI Filters Using Stubs	
2003	Twin-Lead J-Pole Design	
2004	Antenna Impedance Models – Old and New	✓
2005	Novel and Strange Ideas in Antennas and Impedance Matching	
2006	Novel and Strange Ideas in Antennas and Impedance Matching 2	✓
2007	New Results on Antenna Impedance Models and Matching	✓
2008	Antenna Modeling for Radio Amateurs	✓
2009	(convention held in Reno)	
2010	Facts About SWR, Reflected Power, and Power Transfer on Real Transmission Lines with Loss	
2011	Conjugate Match Myths	✓
2012	Transmission Line Filters Beyond Stubs and Traps	✓

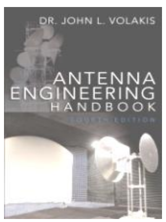
Topics

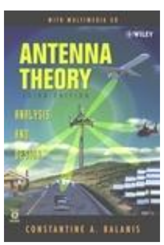
- **Antenna books**
- **Software for modeling antennas and circuits**
- **What motivated this talk**
  - General Class License question G7C06
  - K6OIK 2-meter pager rejection filter presented in 2002
  - RFI mitigation for multi-station operations at Field Day
- **Transmission line and stub properties**
- **Lossless, reflection filters**
  - Simple trap
  - Filters having multiple pass and rejection frequencies
  - Variety of useful RFI filters for Amateur operations
  - Sub-band filters for Field Day
- **Sub-harmonic stub filters**
- **Reflectionless stub filters**
- **Commensurate stub filters**
- **Re-entrant filters**
- **References**

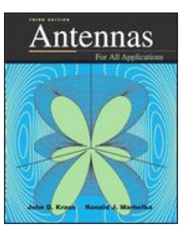
Favorite Antenna Books





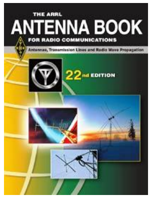


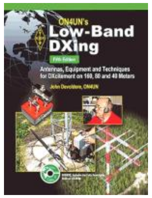


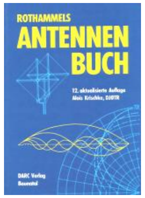


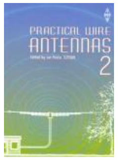
- **Books for antenna engineers and students**
  - R.C. Hansen and R.E. Collin, *Small Antenna Handbook*, Wiley, 2011, ISBN 0470890835
  - *Modern Antenna Handbook*, C.A. Balanis editor, Wiley, 2008, ISBN 0470036346
  - *Antenna Engineering Handbook*, 4^{th} ed., J.L. Volakis editor, McGraw-Hill, 2007, ISBN 0071475745. First published in 1961, Henry Jasik editor
  - C.A. Balanis, *Antenna Theory*, 3^{rd} ed., Wiley, 2005, ISBN 047166782X. First published in 1982 by Harper & Row
  - J.D. Kraus and R.J. Marhefka, *Antennas*, 3^{rd} ed., McGraw-Hill, 2001, ISBN 0072321032. First published in 1950
  - S.J. Orfanidis, *Electromagnetic Waves and Antennas*, draft textbook online at http://www.ece.rutgers.edu/~orfanidi/ewa/
  - E.A. Laport, *Radio Antenna Engineering*, McGraw-Hill, 1952 http://snulbug.mtview.ca.us/books/RadioAntennaEngineering
  - G.V. Ayzenberg, *Shortwave Antennas*, 1962, transl. from Russian, DTIC AD0706545. http://www.dtic.mil/dtic/tr/fulltext/u2/706545.pdf
- **Antenna research papers**
  - IEEE AP-S Digital Archive, 2001-2009 (1 DVD), JD0307
  - IEEE AP-S Digital Archive, 2001-2006 (1 DVD), JD0304
  - IEEE AP-S Digital Archive, 2001-2003 (1 DVD), JD0301
  - IEEE AP-S Digital Archive, 1952-2000 (2 DVDs), JD0351

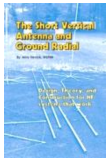
Favorite Antenna Books continued

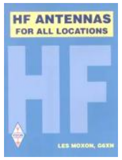




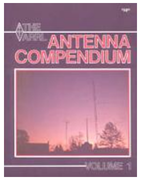


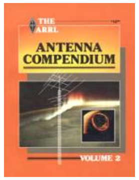


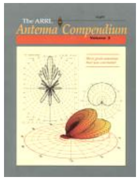
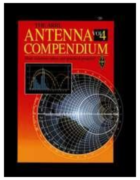


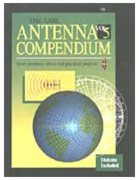


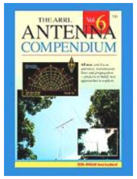
- **Books for Radio Amateurs**
  - *ARRL Antenna Book*, 22nd ed., H.W. Silver (N0AX) editor, American Radio Relay League, 2011, ISBN 087259694X
  - J. Devoldere (ON4UN), *ON4UN's Low-Band Dxing*, 5th ed., American Radio Relay League, 2011, ISBN 087259856X
  - *Rothammel's Antennenbuch*, 12th ed., A. Krischke (DJ0TR) editor, DARC Verlag, 2006, ISBN 388692033X
  - *Practical Wire Antennas 2*, I. Poole (G3YWX) editor, Radio Society of Great Britain, 2005, ISBN 1905086040
  - J. Sevick (W2FMI), *The Short Vertical Antenna and Ground Radial*, CQ Communications, 2003, ISBN 0943016223
  - L. Moxon (G6XN), *HF Antennas for All Locations*, 2nd ed., Radio Society of Great Britain, 1983, ISBN 1872309151
- **ARRL Antenna Compendium series – Volumes 1 through 8**

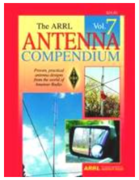


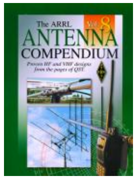


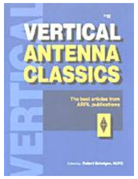


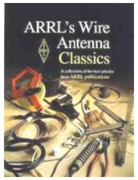


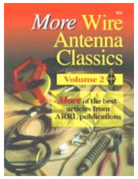


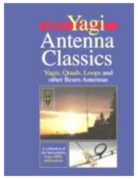


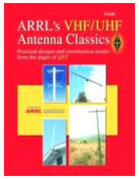
- **ARRL Antenna Classics series – six titles**

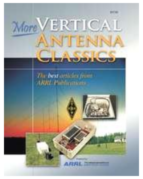




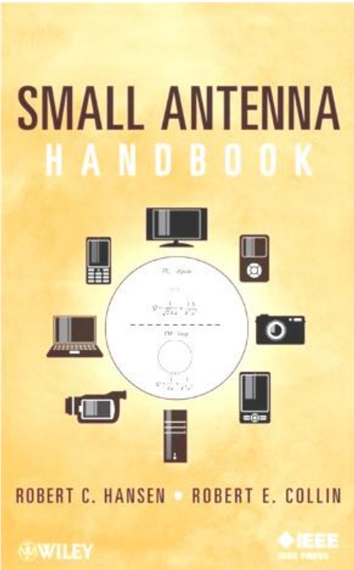




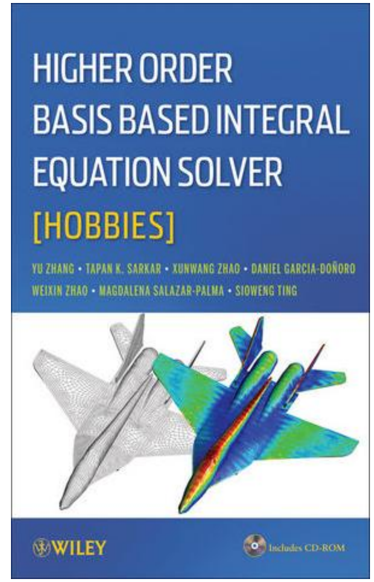




New Antenna Books of Interest

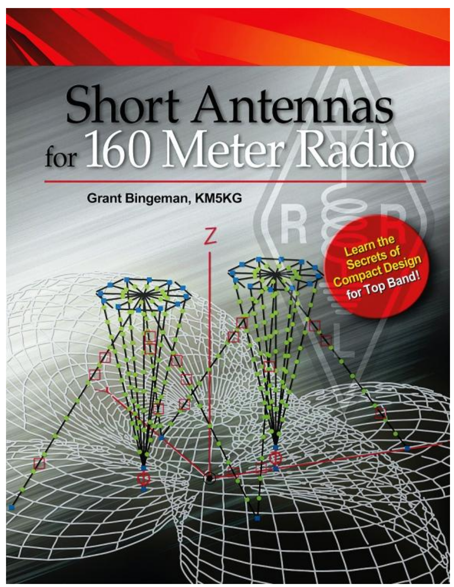


R.C. Hansen and R.E. Collin, *Small Antenna Handbook*, Wiley, 2011, ISBN 0470890835

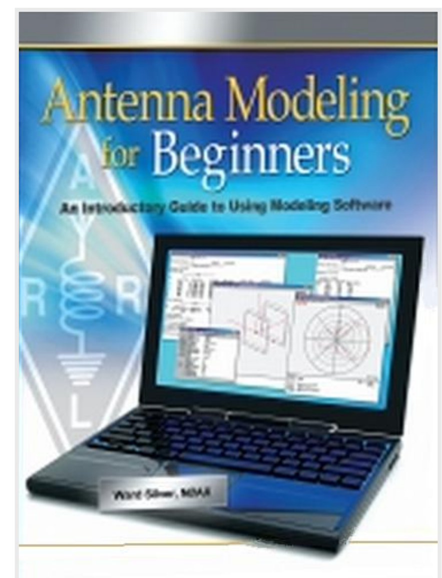


Y. Zhang et al., *Higher Order Basis Based Integral Equation Solver* [*HOBBIES*], Wiley, 2012, ISBN 1118140656

G. Bingeman, KM5KG, *Short Antennas for 160 Meter Radio*, ARRL, 2012, ISBN 9780872595798



H.W. Silver, N0AX, *Antenna Modeling for Beginners*, ARRL, 2012, ISBN 9780872593961

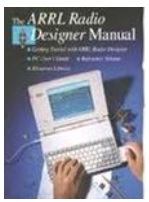


Software

Antenna Modeling Programs for Radio Amateurs

- ***EZNEC*** **http://www.eznec.com**
  - EZNEC v.5 demo program Free
  - EZNEC-ARRL v.3 & v.4 $50 (on ARRL Antenna Book CD-ROM)
  - EZNEC v.5 $90
  - EZNEC+ v.5 $140
  - EZNEC Pro/2 v.5 $500
  - EZNEC Pro/4 v.5 $650 (sold only to NEC-4 licensees)
- ***4nec2*** **http://home.ict.nl/~arivoors/**
  - Free, 11,000 segments, two optimizers
- ***NEC-4*** **https://ipo.llnl.gov/data/assets/docs/nec.pdf**
  - Noncommercial user license $300
- ***FEKO Lite*** **http://www.feko.info**
  - Free LITE version
- ***WIPL-D Lite*** **http://www.wipl-d.com**
  - Free Demo version, more capable Lite version from Artech House $450
- ***HOBBIES*** **http://em-hobbies.com**
  - Similar to WIPL-D Lite but more capability, $162 to $210

General RF Circuit Design, Analysis, and Optimization



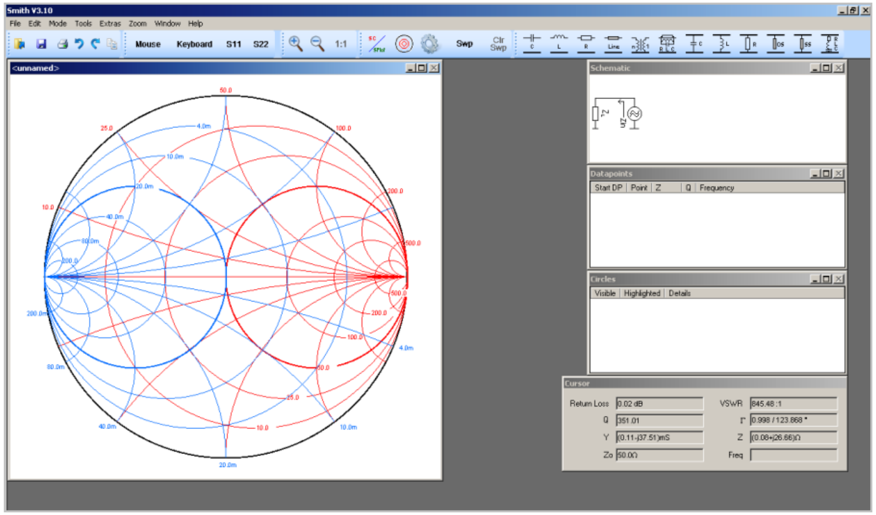
- **Software for Radio Amateurs**
  - *Quite Universal Circuit Simulator* (QUCS) 0.0.16, 2011, $0 (free)
    - Download from http://qucs.sourceforge.net
  - *Ansoft Serenade SV* 8.5 (student version), Ansoft, 2000, $0 (free). No longer available.
  - *ARRL Radio Designer* 1.5, ARRL, 1995. No longer available.
- **Professional electronic design automation (EDA) software**
  - *Advanced Design System* (ADS), Agilent
  - *Microwave Office* (MWO), Applied Wave Research
  - *Designer*, ANSYS

Software for Smith Charting and Network Design

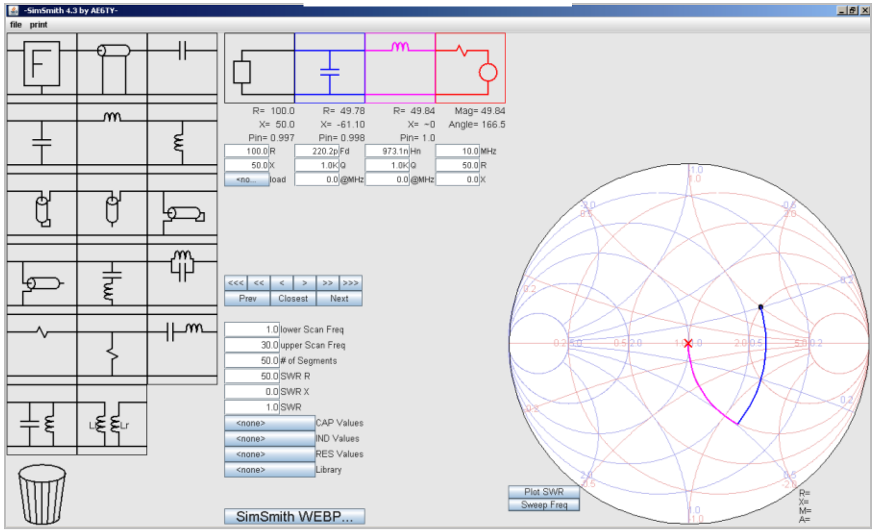
- **Match network analysis with Smith Chart display**
  - *SimSmith* by Ward Harriman AE6TY, 2011, $0 (free)
    - Download from http://ae6ty.com/Smith_Charts.html
  - *Smith* by Fritz Dellsperger HB9AJY, 2010, $0 (free)
    - Download from http://fritz.dellsperger.net
  - *QuickSmith* by Nathan Iyer KJ6FOJ, 2009, $0 (free)
    - Download from http://www.nathaniyer.com/qsdw.htm
  - *linSmith* by James Coppens ON6JC/LW3HAZ, $0 (free)
    - Download from http://jcoppens.com/soft/linsmith/index.en.php
  - *SuperSmith* by J. Bromley K7JEB and J. Tonne W4ENE, $0 (free)
    - Download from http://www.tonnesoftware.com/supersmith.html
  - *XLZIZL* by Dan Maguire AC6LA, 2005. No longer available.
  - *WinSMITH* 2.0, Noble Publishing, 1995. No longer available.
  - *MicroSmith* 2.3, ARRL, 1992. No longer available.

Smith Chart Programs for Ladder Network Design

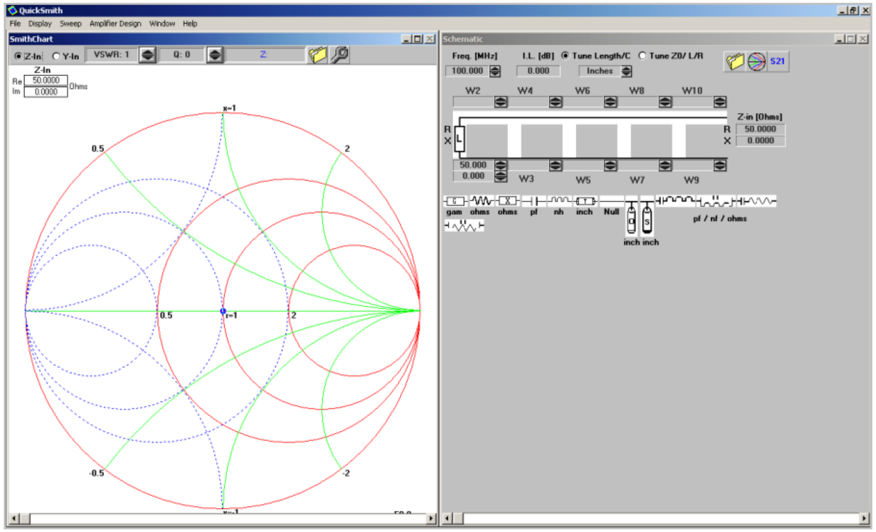
Smith 3.10



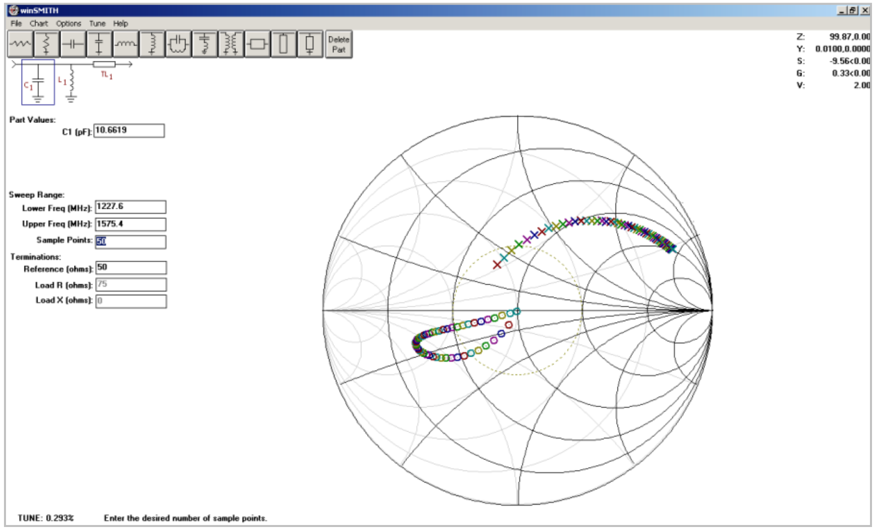
SimSmith 4.4



QuickSmith 4.5



winSMITH 2.0



Questions for 2012

- Given: Several frequencies, rationally related and relatively prime, divided into "pass" and "stop" sets
- Goal: A filter that passes the pass frequencies and rejects the stop frequencies
- For the following questions, assume the filter is made using stubs made from lossless line
- Q1: What is the smallest number of stubs needed?
- Q2: What is the smallest number of distinct characteristic impedances needed?
- Q3: What is the smallest input SWR that can be achieved across all frequencies?
- Q4: What is the smallest total line length needed?

Answers

- **Q1: What is the smallest number of stubs needed?**
  - Answer is one
    $\Rightarrow$ sub-harmonic stub filter
- **Q2: What is the smallest number of distinct characteristic impedances needed?**
  - Answer is one
    $\Rightarrow$ sub-harmonic stub filter
    $\Rightarrow$ non-commensurate stub filter
- **Q3: What is the smallest input SWR that can be achieved across all frequencies?**
  - Answer is one (1:1)
    $\Rightarrow$ reflectionless complementary stub filter
- **Q4: What is the smallest total line length needed?**
  - Answer is zero, or more precisely, arbitrarily small
    $\Rightarrow$ commensurate stub filter

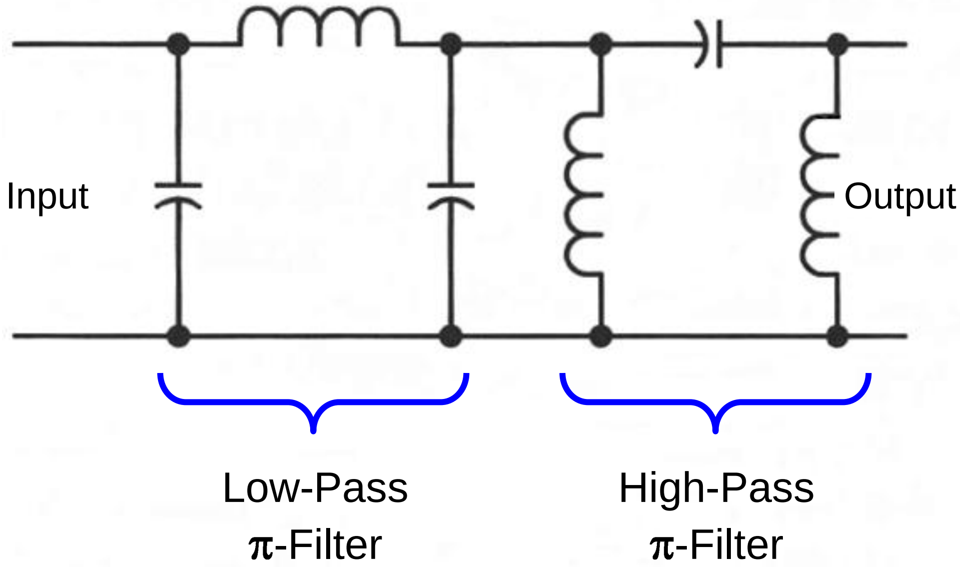
Why This Talk?

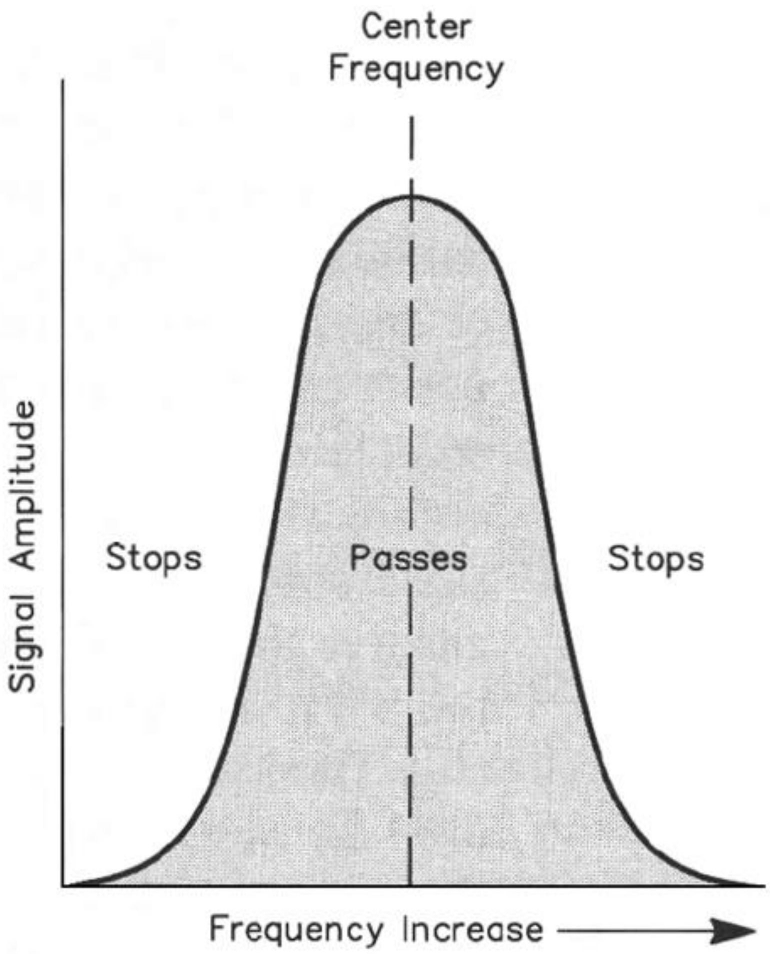
Question G7C06

- **What should be the impedance of a low-pass filter as compared to the impedance of the transmission line into which it is inserted?**
  - A. Substantially higher
  - **B. About the same**
  - C. Substantially lower
  - D. Twice the transmission line impedance

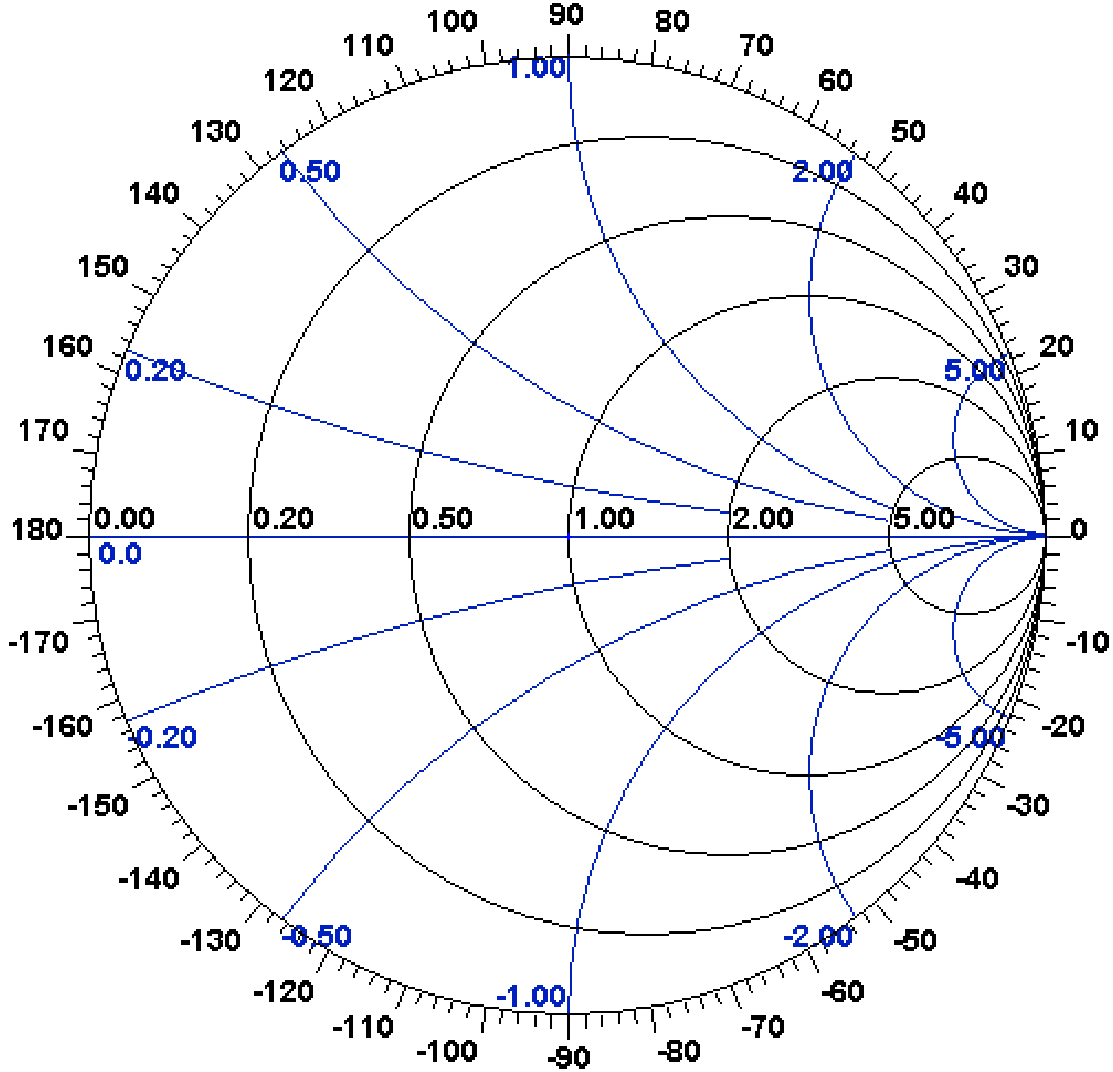
For reflection filters, the answer is true only in the passband
For dissipation filters the answer can be true in general.

A Band-Pass Reflection Filter



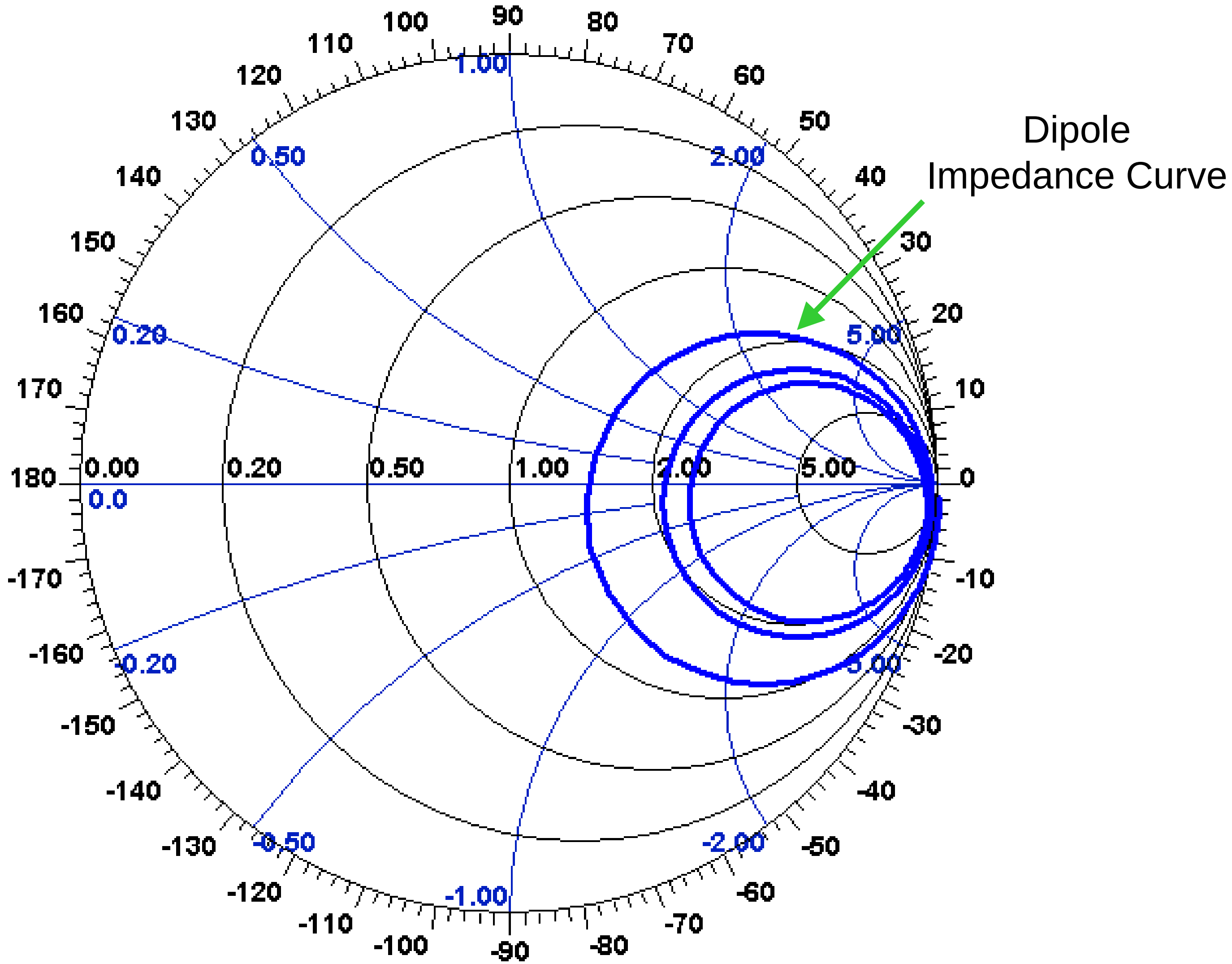


Smith Chart



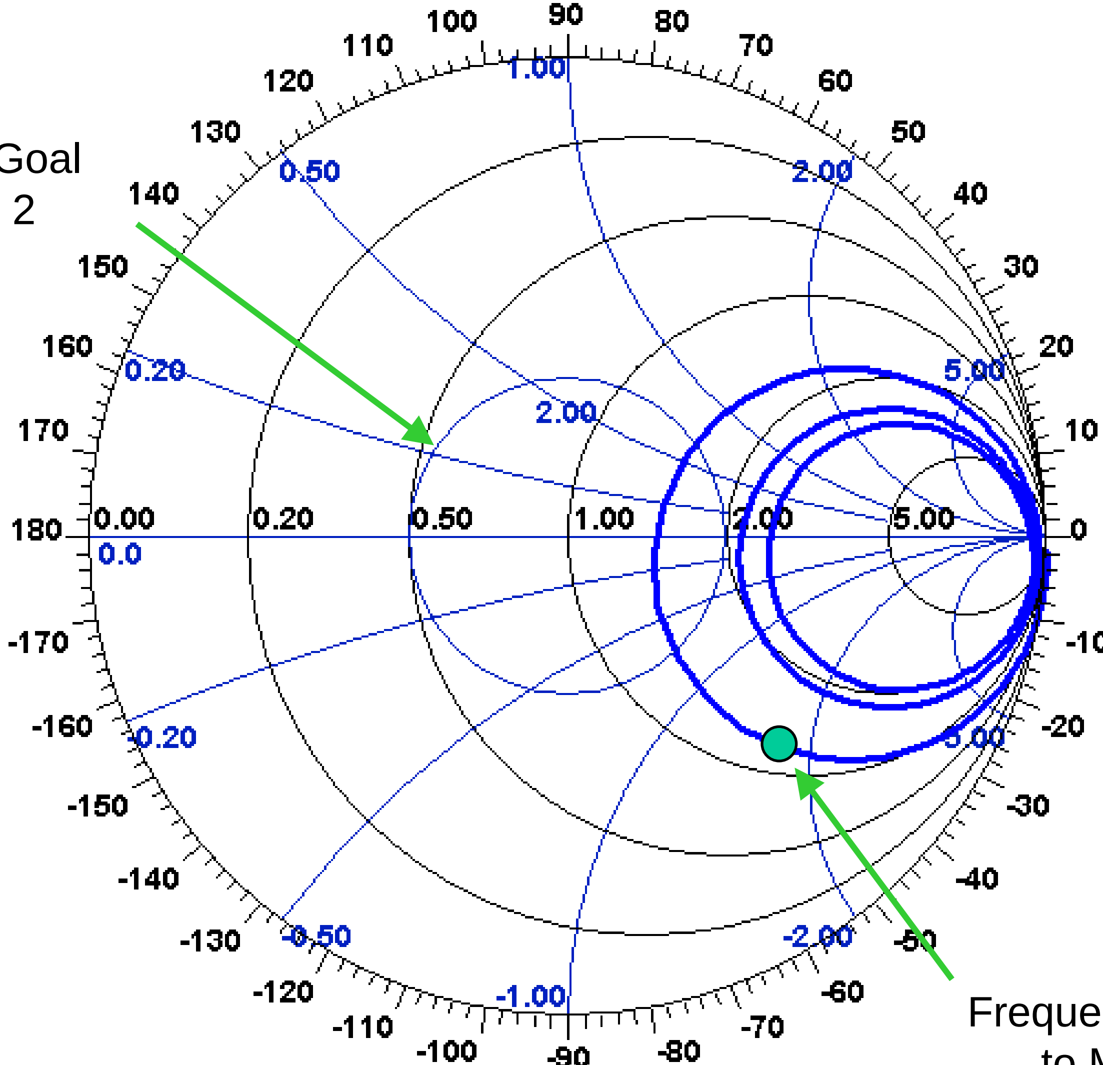
90
80
100
70
110
60
120
50
130
40
140
30
150
20
160
10
170
0
180
-10
-170
-20
-160
-30
-150
-40
-140
-50
-130
-60
-120
-70
-110
-80
-100
-90
1.00
0.50
2.00
0.20
5.00
0.00
0.20
0.50
1.00
2.00
5.00
0.0
-0.20
-5.00
-0.50
-2.00
-1.00

Smith Chart + Data



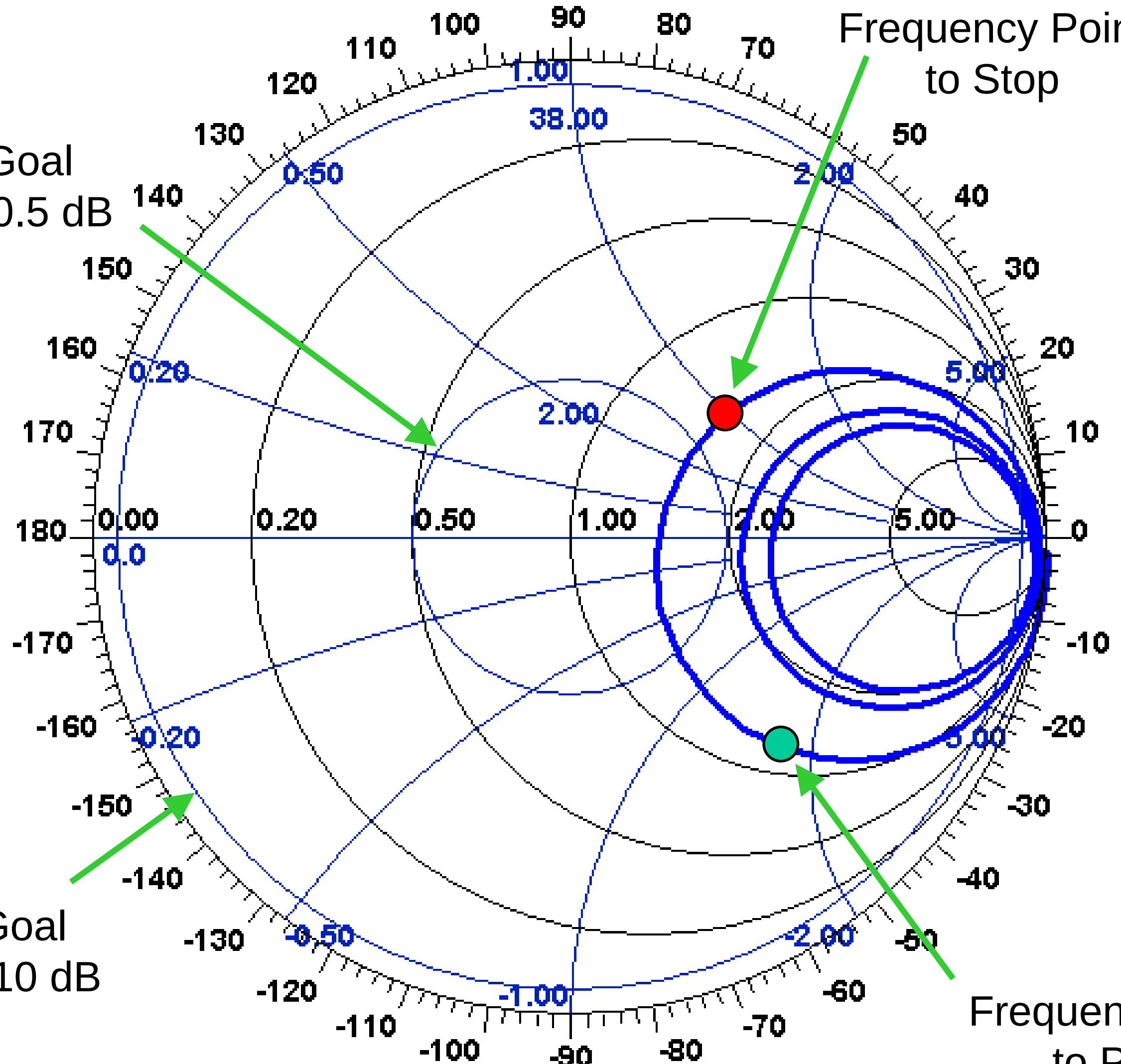
Smith Chart + Data + Match Goal

Match Goal
SWR < 2



Frequency Point
to Match

Smith Chart + Data + Filter Goals



Some Transmission Line Properties

Characteristic Impedance

- **Transmission line characteristic impedance is a useful design variable**
- **For high-frequency applications (UHF), microstrip and stripline can be fabricated for a continuous range of impedances depending on trace width**
- **Coax can be obtained with discrete values of characteristic impedance from 12.5 to 190 ohms**
- **Additional values of characteristic impedance can be obtained by series or parallel combinations**
  - Lines can be series-connected to sum their characteristic impedances
  - Lines can be parallel-connected to sum their characteristic admittances

Non-50/75 Ohm Coaxial Transmission Lines

Impedance	Types
12.5 Ω	RG192, RG193, RG194
25 Ω	RG73, RG191, RG230, RG328 M17/124
35/37 Ω	RG83, RG100, RG264
93/95 Ω	RG7, RG22, RG43, RG57, RG62, RG71, RG111, RG130, RG131, RG133, RG180, RG294, RG317 M17/15, M17/30, M17/56, M17/90, M17/95, M17/100, M17/137, M17/139, M17/177, M17/178, M17/182, M17/185, M17/195,
100 Ω	RG285, RG287, RG383
125 Ω	RG23, RG24, RG63, RG79, RG89, RG160 M17/16, M17/31, M17/218
140 Ω	RG102
150 Ω	RG72, RG125
185 Ω	RG114 M17/47, M17/208
190 Ω	RG146

Small Diameter Coax Types
0.18 to 0.25 inch O.D. for BNC Connectors

Z_0	Line Types	v.f.	150 MHz dB/100′	150 MHz dB/λ
35 Ω	RG100			
50 Ω	ETS1-50T LMR 300 LMR 240 9258-RG8/X LMR 200 LMR 195 9210-RG58/U 9211-RG58A/U M17/28-RG58	0.82 0.85 0.84 0.82 0.83 0.80 0.66 0.75 0.66	2.20 2.40 3.01 3.85 3.98 4.44 4.67 4.92 5.63	0.118 0.134 0.166 0.207 0.217 0.233 0.202 0.242 0.243
93 Ω	6539Y8-RG62/U 9269-RG62A/U M17/30-RG62 M17/90-RG71 M17/97-RG210 M17/185 M17/195 8255-RG62B/U	0.84 0.84 0.81 0.81 0.85 0.81 0.85 0.84	3.30 3.30 3.50 3.50 3.50 3.50 3.50 3.60	0.182 0.182 0.186 0.186 0.195 0.186 0.195 0.198
95 Ω	M17/177	0.695	7.71	0.351

Larger Diameter Coax Types
0.40 to 0.42 inch O.D. for UHF Connectors

Z_0	Line Types	v.f.	150 MHz dB/100′	150 MHz dB/λ
35 Ω	RG83	0.66	3.46	0.150
50 Ω	LDF2-50 LMR 400 9913-RG8/U 9913F7-RG8/U 9914-RG8 M17/74-RG213	0.88 0.85 0.84 0.83 0.82 0.66	1.28 1.54 1.57 1.78 1.78 2.52	0.074 0.086 0.087 0.097 0.096 0.109
95 Ω	M17/100-RG133 M17/15-RG22 M17/182	0.66 0.66 0.66	2.74 2.81 2.81	0.118 0.122 0.122
125 Ω	9857-RG63/U M17/31-RG63 M17/218	0.84 0.86 0.86	1.92 2.35 2.35	0.106 0.133 0.133
185 Ω	M17/47-RG114 M17/208	0.85 0.83	4.29 4.29	0.239 0.233

Transmission Lines are 2-Port Devices

- **Transmission, Chain, or ABCD matrix**

$$T = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh \gamma l & Z_0 \sinh \gamma l \\ \frac{1}{Z_0} \sinh \gamma l & \cosh \gamma l \end{bmatrix}$$

- **Open-circuit impedance matrix Z**

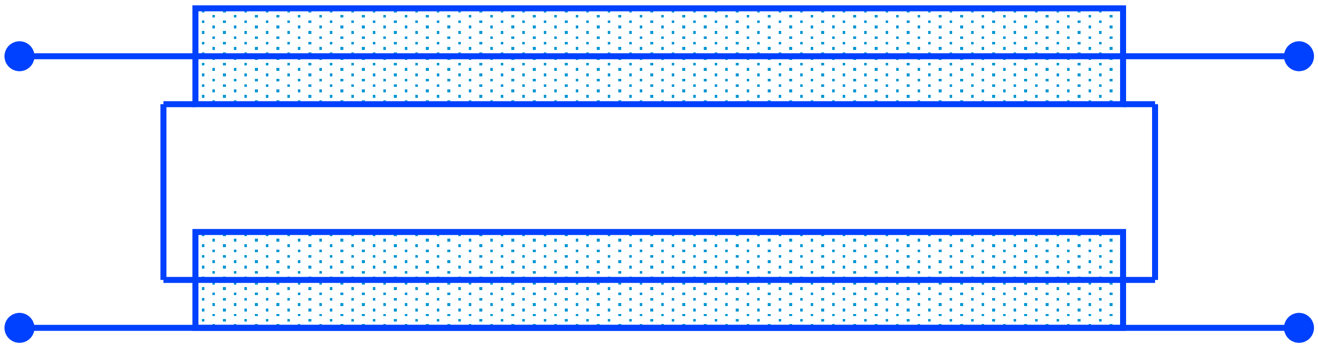
$$Z = \begin{bmatrix} \frac{A}{C} & \frac{1}{C} \\ \frac{1}{C} & \frac{D}{C} \end{bmatrix} = Z_0 \begin{bmatrix} \coth \gamma l & \frac{1}{\sinh \gamma l} \\ \frac{1}{\sinh \gamma l} & \coth \gamma l \end{bmatrix}$$

- **Short-circuit admittance matrix Y**

$$Y = \begin{bmatrix} \frac{D}{B} & \frac{-1}{B} \\ \frac{-1}{B} & \frac{A}{B} \end{bmatrix} = Y_0 \begin{bmatrix} \coth \gamma l & \frac{-1}{\sinh \gamma l} \\ \frac{-1}{\sinh \gamma l} & \coth \gamma l \end{bmatrix}$$

2-Port Series Connection Sums Line Impedances

$$Z_0' = Z_{01} + Z_{02} \quad \text{if} \quad \beta_1 l_1 = \beta_2 l_2$$



- **Make line electrical lengths equal, $\beta_1 l_1 = \beta_2 l_2$**
- **Unbalanced version shown**
  - Keep lines spaced several diameters apart
  - Build as a common-mode choke
  - Put ferrite beads along both shields or wind on a torroid
- **Balanced version is made by joining shields instead**
  - OK if shields touch

Proof

- **When 2-ports are connected so ports are in series, their Z matrices sum**

$$Z = Z_{01}\begin{bmatrix} \coth\gamma_1 l_1 & \dfrac{1}{\sinh\gamma_1 l_1} \\ \dfrac{1}{\sinh\gamma_1 l_1} & \coth\gamma_1 l_1 \end{bmatrix} + Z_{02}\begin{bmatrix} \coth\gamma_2 l_2 & \dfrac{1}{\sinh\gamma_2 l_2} \\ \dfrac{1}{\sinh\gamma_2 l_2} & \coth\gamma_2 l_2 \end{bmatrix}$$

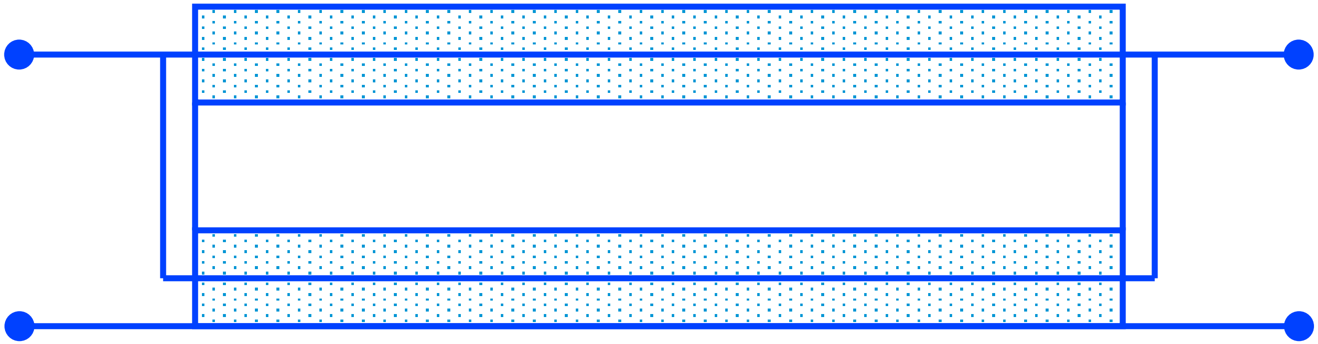
$$= (Z_{01} + Z_{02})\begin{bmatrix} \coth\gamma l & \dfrac{1}{\sinh\gamma l} \\ \dfrac{1}{\sinh\gamma l} & \coth\gamma l \end{bmatrix}$$

- **Characteristic impedances of series connected lines sum if $\beta_1 l_1 = \beta_2 l_2$**

$$Z_0' = Z_{01} + Z_{02}$$

2-Port Parallel Connection Sums Line Admittances

$$Z_0' = \frac{1}{\frac{1}{Z_{01}} + \frac{1}{Z_{02}}} \quad \text{if} \quad \beta_1 l_1 = \beta_2 l_2$$



- **Make line electrical lengths equal, $\beta_1\, l_1 = \beta_2\, l_2$**
- **Unbalanced version shown**
  - OK if shields touch
- **Balanced version is made by joining each line's center to other line's shield instead**
  - Keep lines several diameters apart

Proof

- **When 2-ports are connected so ports are in parallel, their Y matrices sum**

$$Y = Y_{01}\begin{bmatrix} \coth\gamma_1 l_1 & \dfrac{-1}{\sinh\gamma_1 l_1} \\ \dfrac{-1}{\sinh\gamma_1 l_1} & \coth\gamma_1 l_1 \end{bmatrix} + Y_{02}\begin{bmatrix} \coth\gamma_2 l_2 & \dfrac{-1}{\sinh\gamma_2 l_2} \\ \dfrac{-1}{\sinh\gamma_2 l_2} & \coth\gamma_2 l_2 \end{bmatrix}$$

$$= (Y_{01} + Y_{02})\begin{bmatrix} \coth\gamma l & \dfrac{-1}{\sinh\gamma l} \\ \dfrac{-1}{\sinh\gamma l} & \coth\gamma l \end{bmatrix}$$

- **Characteristic admittances of parallel connected lines sum if $\beta_1 l_1 = \beta_2 l_2$**

$$Z_0' = \frac{1}{Y_0'} = \frac{1}{Y_{01} + Y_{02}} = \frac{1}{\dfrac{1}{Z_{01}} + \dfrac{1}{Z_{02}}}$$

Impedance of Transmission Line Stubs

- **Terminated general transmission lines**

$$Z_{in} = Z_0 \frac{Z_L \cosh \gamma l + Z_0 \sinh \gamma l}{Z_L \sinh \gamma l + Z_0 \cosh \gamma l}$$

- **Terminated lossless lines with unity velocity factor**

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan \frac{2\pi f l}{c}}{Z_0 + jZ_L \tan \frac{2\pi f l}{c}}$$

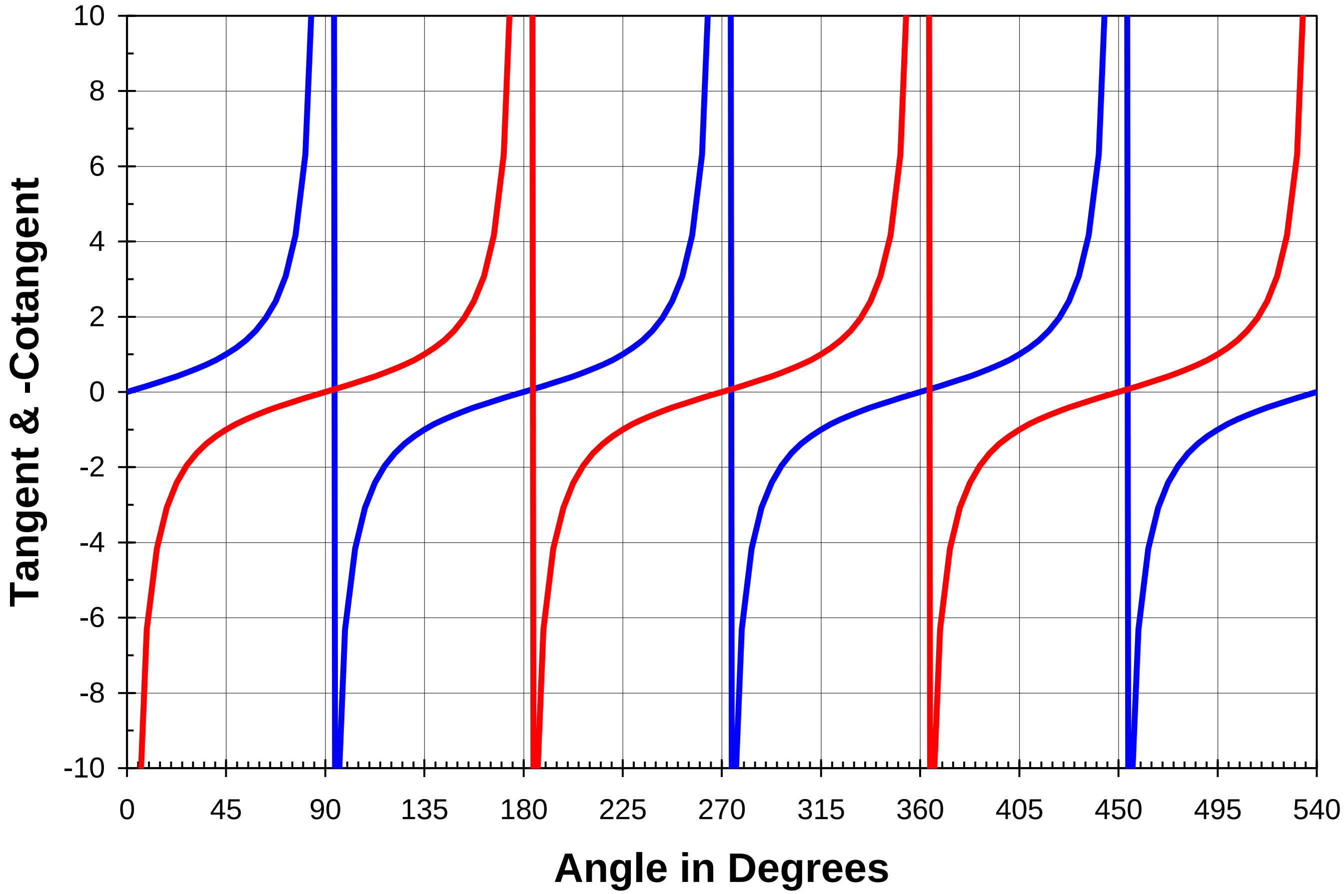
- **Short-circuited stub reactance and susceptance**

$$Z_{in} = jZ_0 \tan \frac{2\pi f l}{c} \qquad Y_{in} = -jY_0 \cot \frac{2\pi f l}{c}$$

- **Open-circuited stub reactance and susceptance**

$$Z_{in} = -jZ_0 \cot \frac{2\pi f l}{c} \qquad Y_{in} = jY_0 \tan \frac{2\pi f l}{c}$$

Graph of Tangent and –Cotangent Functions



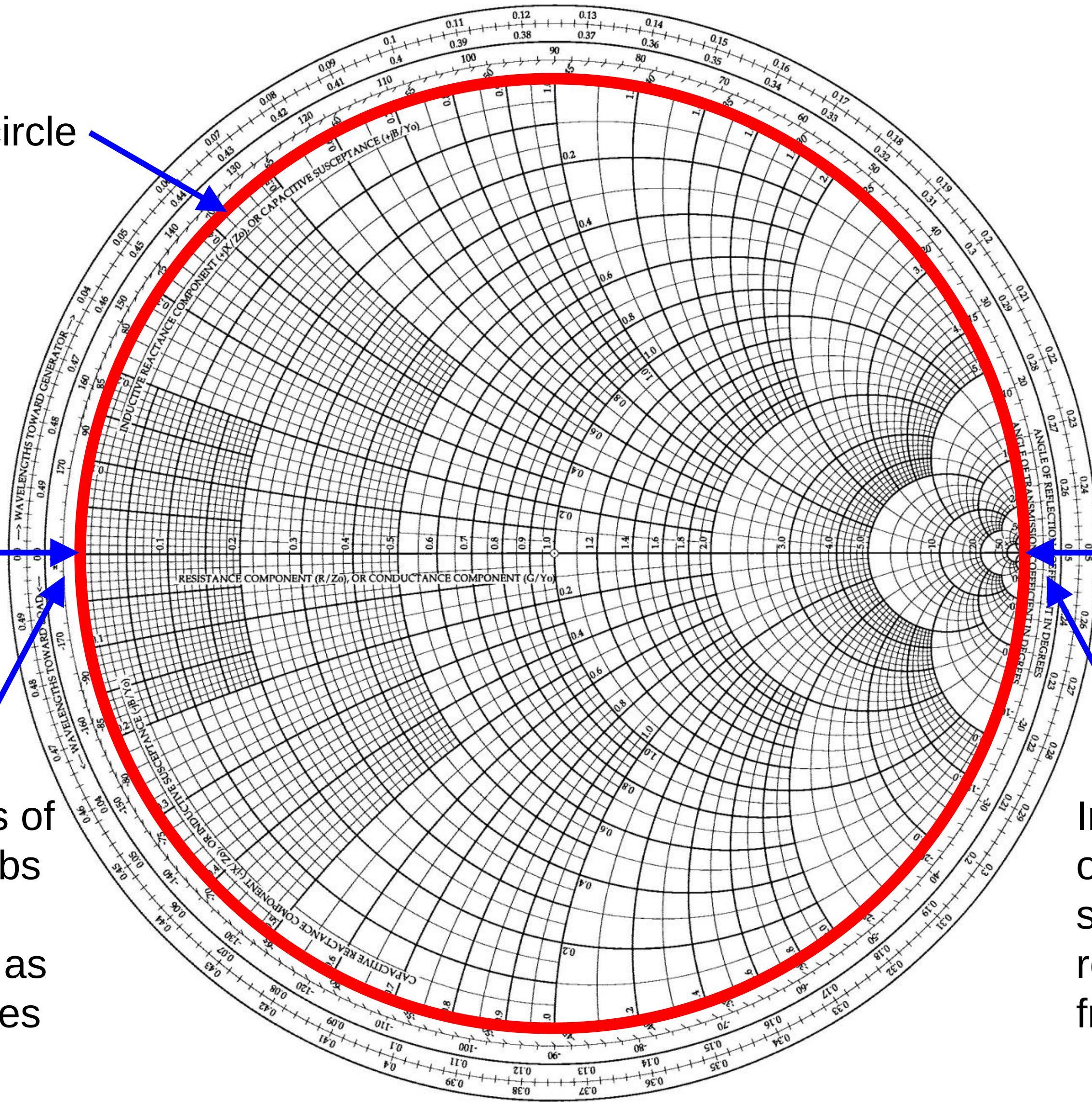
Foster's Reactance Theorem requires that reactance and susceptance of lossless devices and networks have positive slopes.

Smith Chart

r = 0, *g* = 0 circle

Zero impedance
Infinite admittance

Infinite impedance
Zero admittance



Impedance curves of short-circuited stubs start at zero and revolve clockwise as frequency increases

Impedance curves of open-circuited stubs start at infinity and revolve clockwise as frequency increases

Electrically-Short Stubs As Capacitors and Inductors

- **Open and shorted stubs that are electrically short act like lumped element capacitors and inductors**
- **Electrically-short short-circuited stubs act as inductors**

$$Z_{in} = jZ_0 \tan \frac{2\pi f l}{c} \approx j\, 2\pi f \, \frac{Z_0\, l}{c} \qquad \Rightarrow \qquad \boxed{L = \frac{Z_0\, l}{c} = Z_0\, \tau}$$

- **Electrically-short open-circuited stubs act as capacitors**

$$Z_{in} = -jZ_0 \cot \frac{2\pi f l}{c} \approx \frac{1}{j\, 2\pi f \, \dfrac{l}{Z_0\, c}} \qquad \Rightarrow \qquad \boxed{C = \frac{l}{Z_0\, c} = \frac{\tau}{Z_0}}$$

- **Stubs may be used in place of capacitors and inductors to make filters**

Capacitance and Inductance

- Set C and L by changing both Z_0 and l
- Set C and L by changing Z_0 with l fixed
- Set C and L by changing l with Z_0 fixed

Z_0	Short-Circuited Stubs nH per ft	Open-Circuited Stubs pF per ft
12.5	12.7	81.3
25	25.4	40.7
37.5	38.1	27.1
50	50.8	20.3
75	76.2	13.6
100	102	10.2
150	152	6.78
200	203	5.08

Quarter-Wave Stubs As Resonant Circuits

- Quarter-wave stubs act like resonant LC circuits
- Short-circuited stubs act like parallel resonant circuits

$$Z_{in} = jZ_0 \tan\frac{\pi}{2}\frac{f}{f_0} \quad \Rightarrow \quad \boxed{L = \frac{2Z_0}{\pi^2 f_0} \quad C = \frac{1}{8Z_0 f_0}}$$

- Open-circuited stubs act like series-resonant circuits

$$Z_{in} = -jZ_0 \cot\frac{\pi}{2}\frac{f}{f_0} \quad \Rightarrow \quad \boxed{L = \frac{Z_0}{8 f_0} \quad C = \frac{2}{\pi^2 Z_0 f_0}}$$

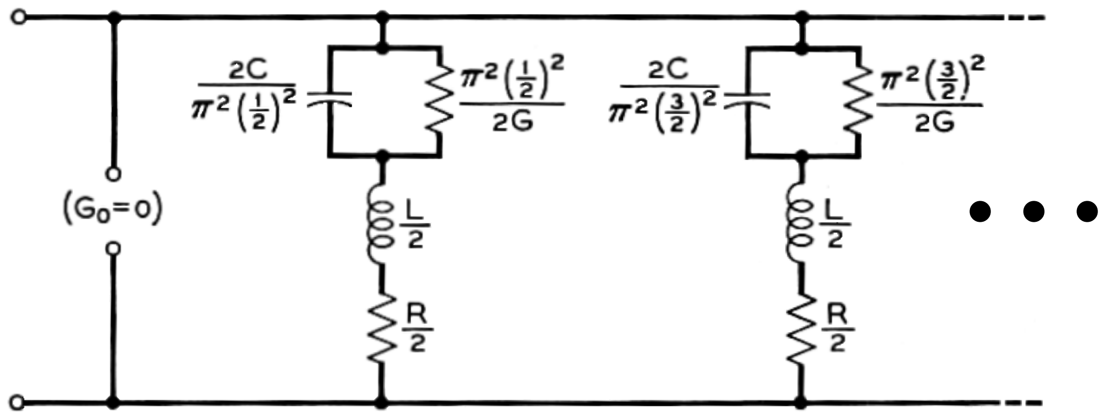
Exact 1-Port Equivalent Circuits of an Open Stub

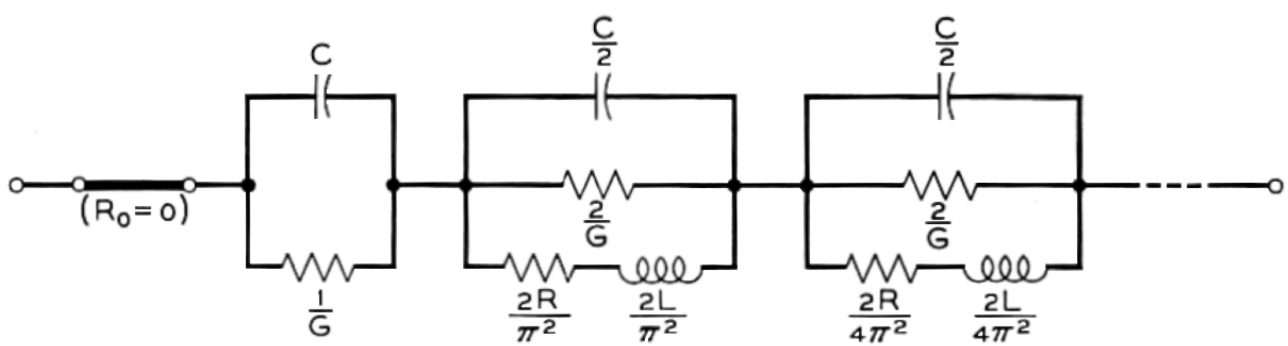
$$Z_{in} = Z_0 \coth \gamma l = Z_0 \coth(\alpha l + j\beta l)$$

Constant, frequency-independent loss
R, *L*, *G*, *C* are for total line length *l*

$$L = Z_0 \frac{l}{c} = Z_0 \tau$$

$$C = \frac{l}{Z_0 c} = \frac{\tau}{Z_0}$$





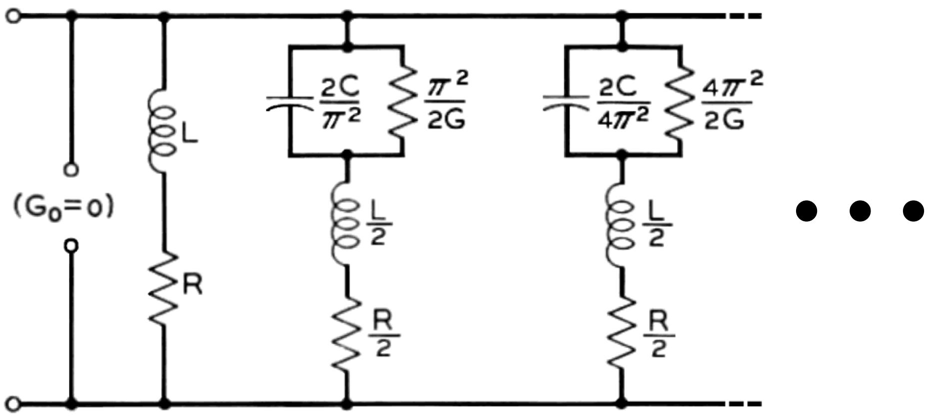
Exact 1-Port Equivalent Circuits of a Shorted Stub

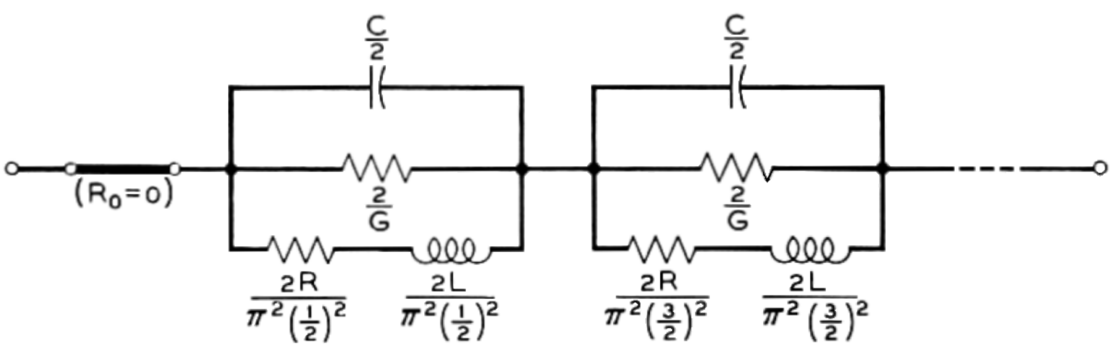
$$Z_{in} = Z_0 \tanh \gamma l = Z_0 \tanh(\alpha l + j\beta l)$$

Constant, frequency-independent loss
R, *L*, *G*, *C* are for total line length *l*

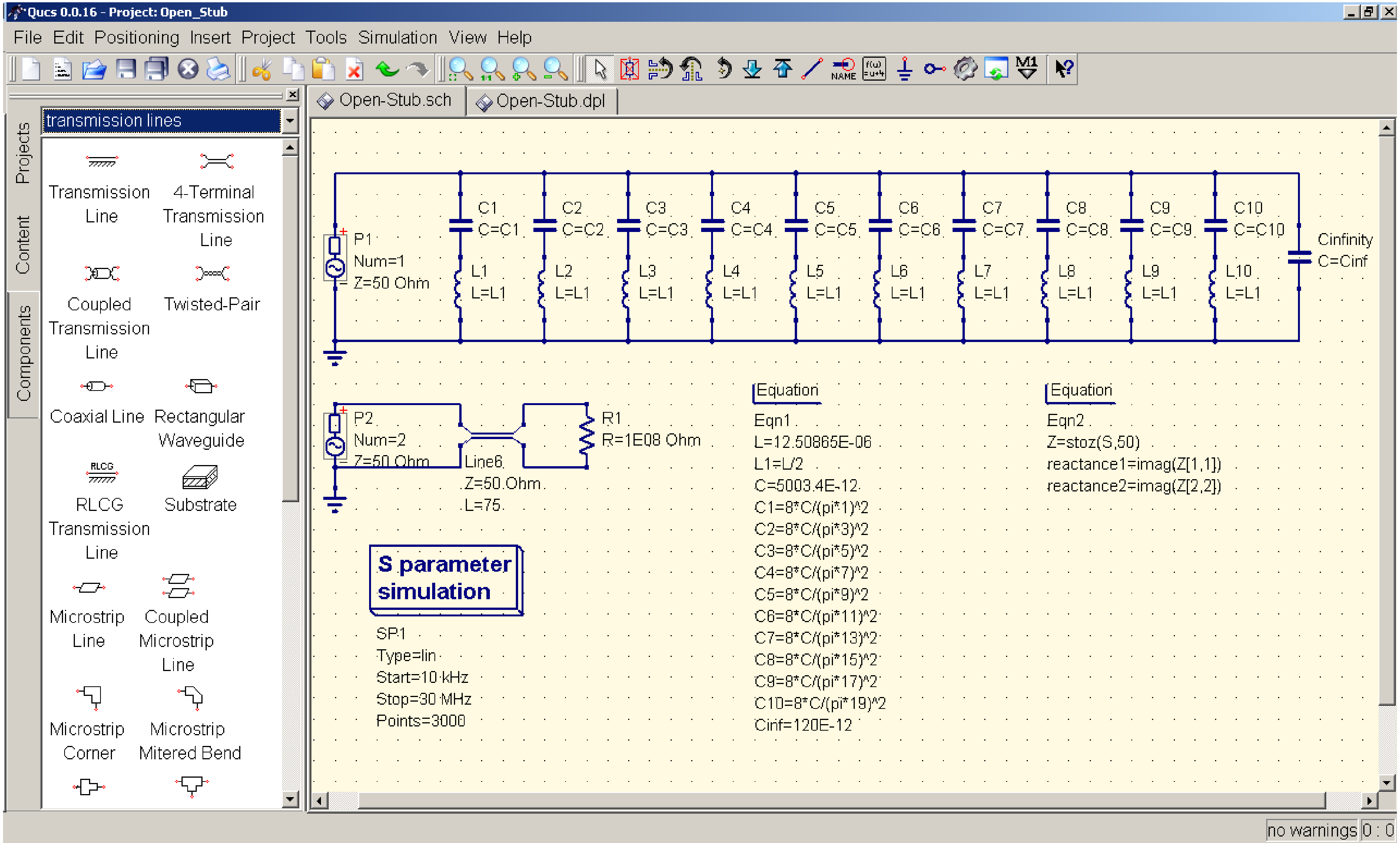
$$L = Z_0 \frac{l}{c} = Z_0 \tau$$

$$C = \frac{l}{Z_0 c} = \frac{\tau}{Z_0}$$

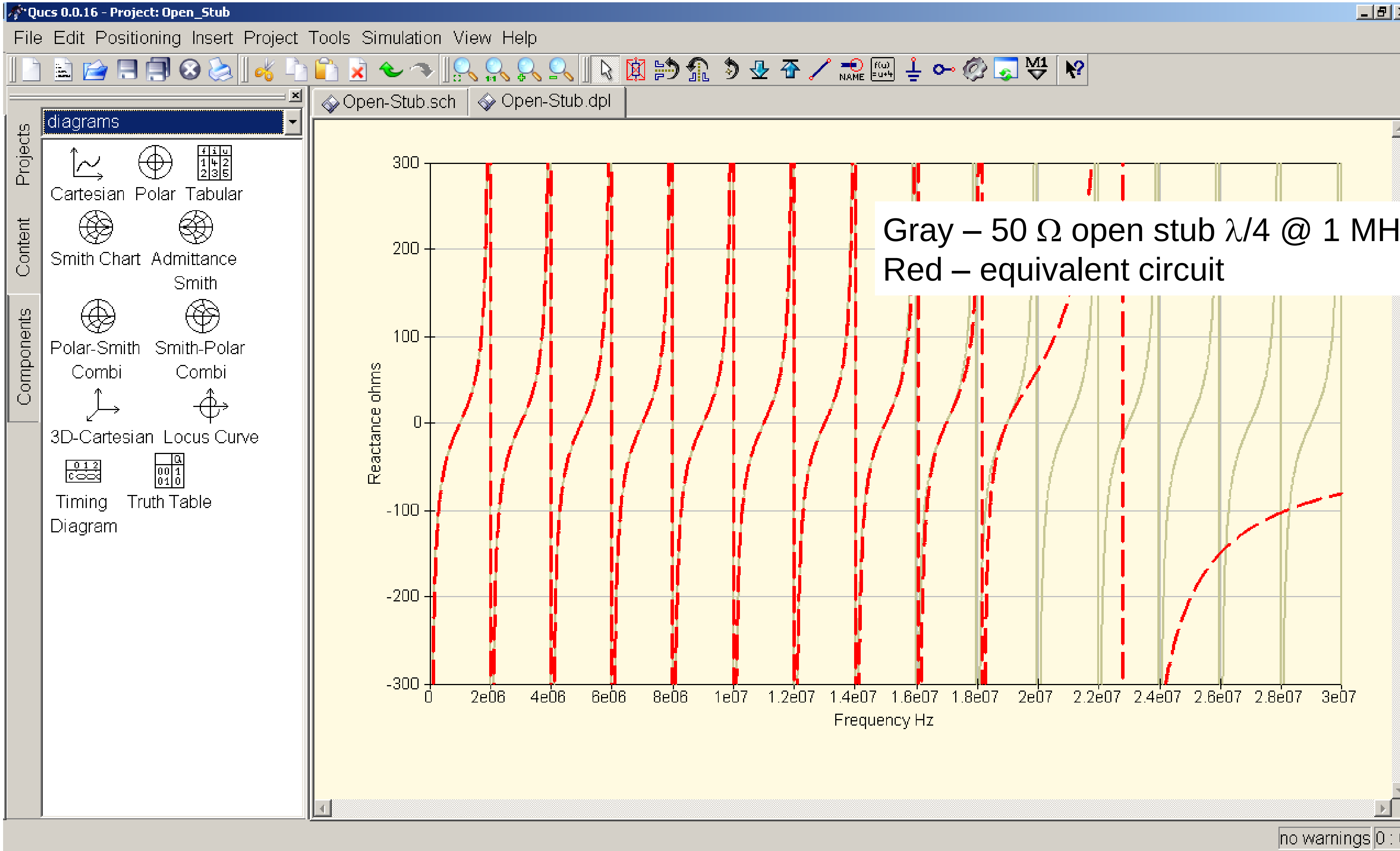




Evaluation of Broadband Open Stub Model in QUCS

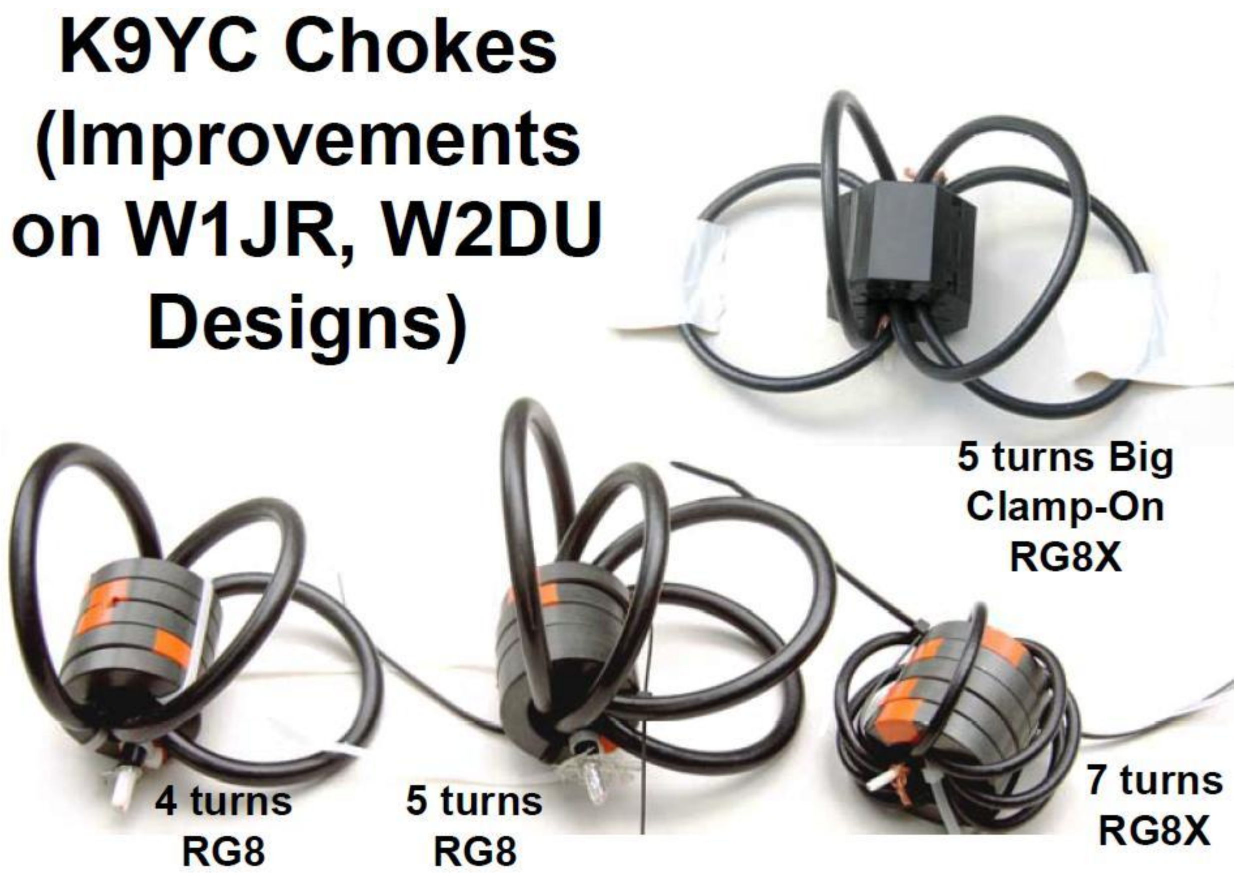


Broadband Open Stub Model for 0 – 19 MHz



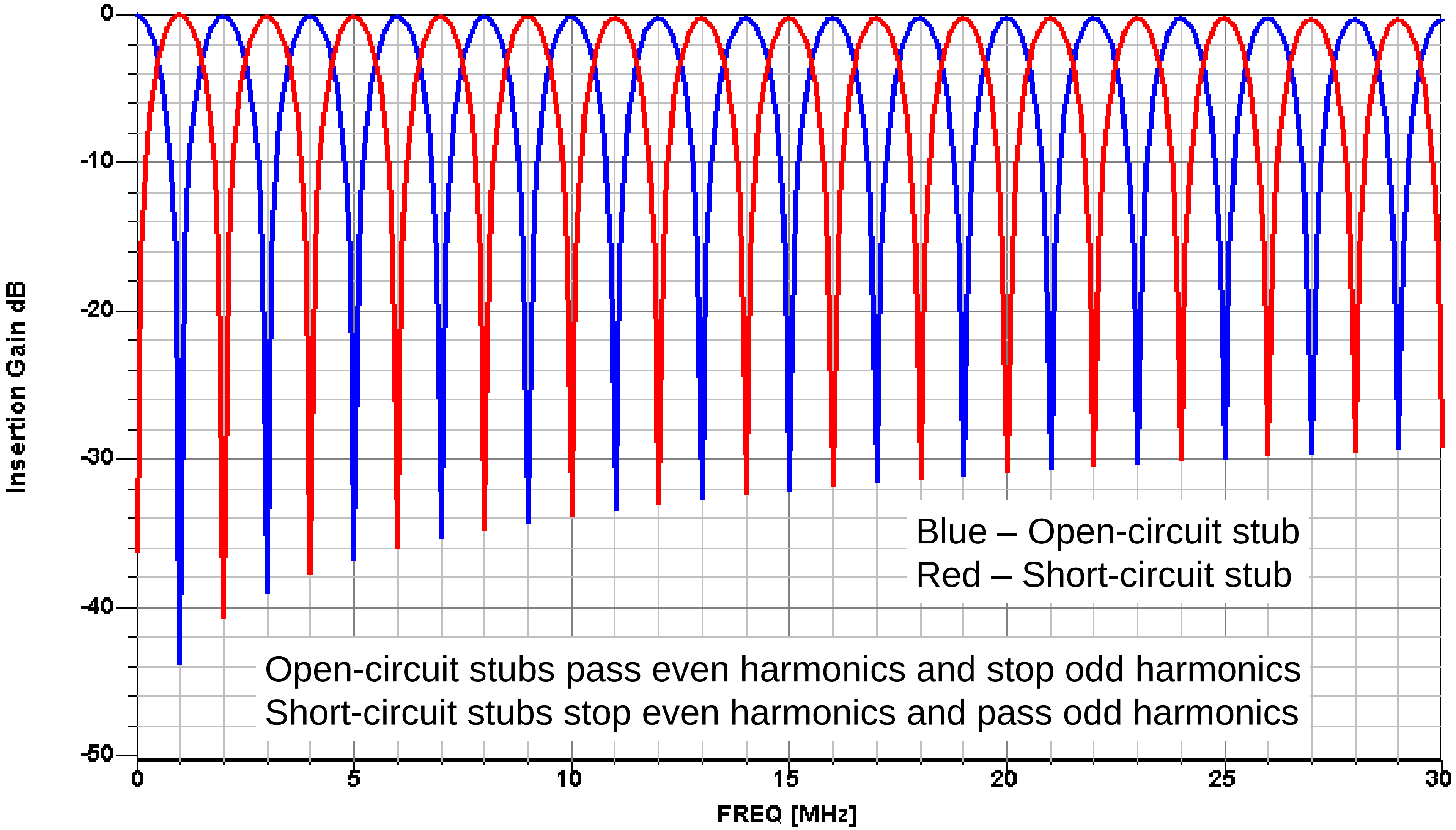
Floating Stubs

- Some stubs may need to float, e.g. series stubs
- Floating stubs require common mode chokes

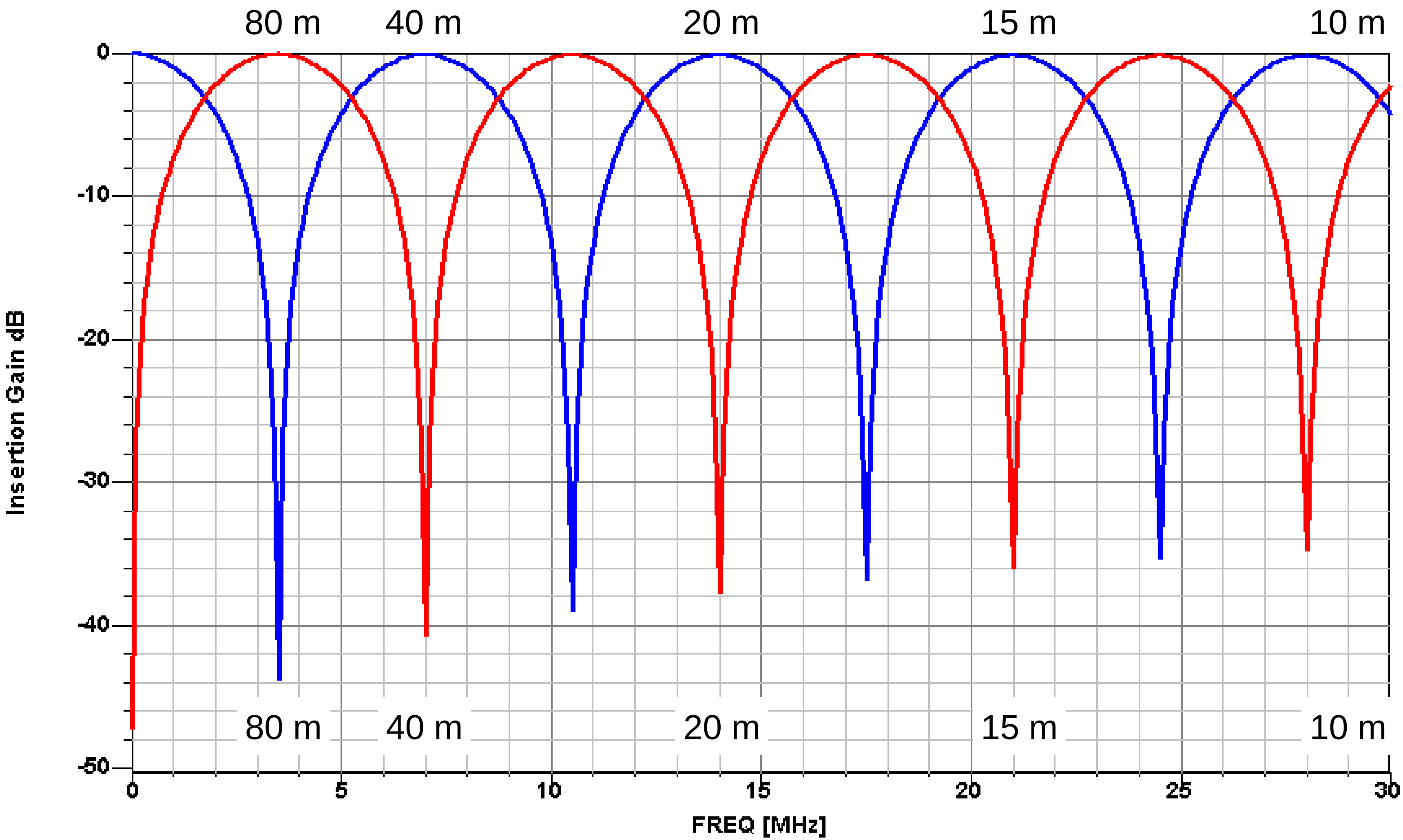


Transmission Line Filters

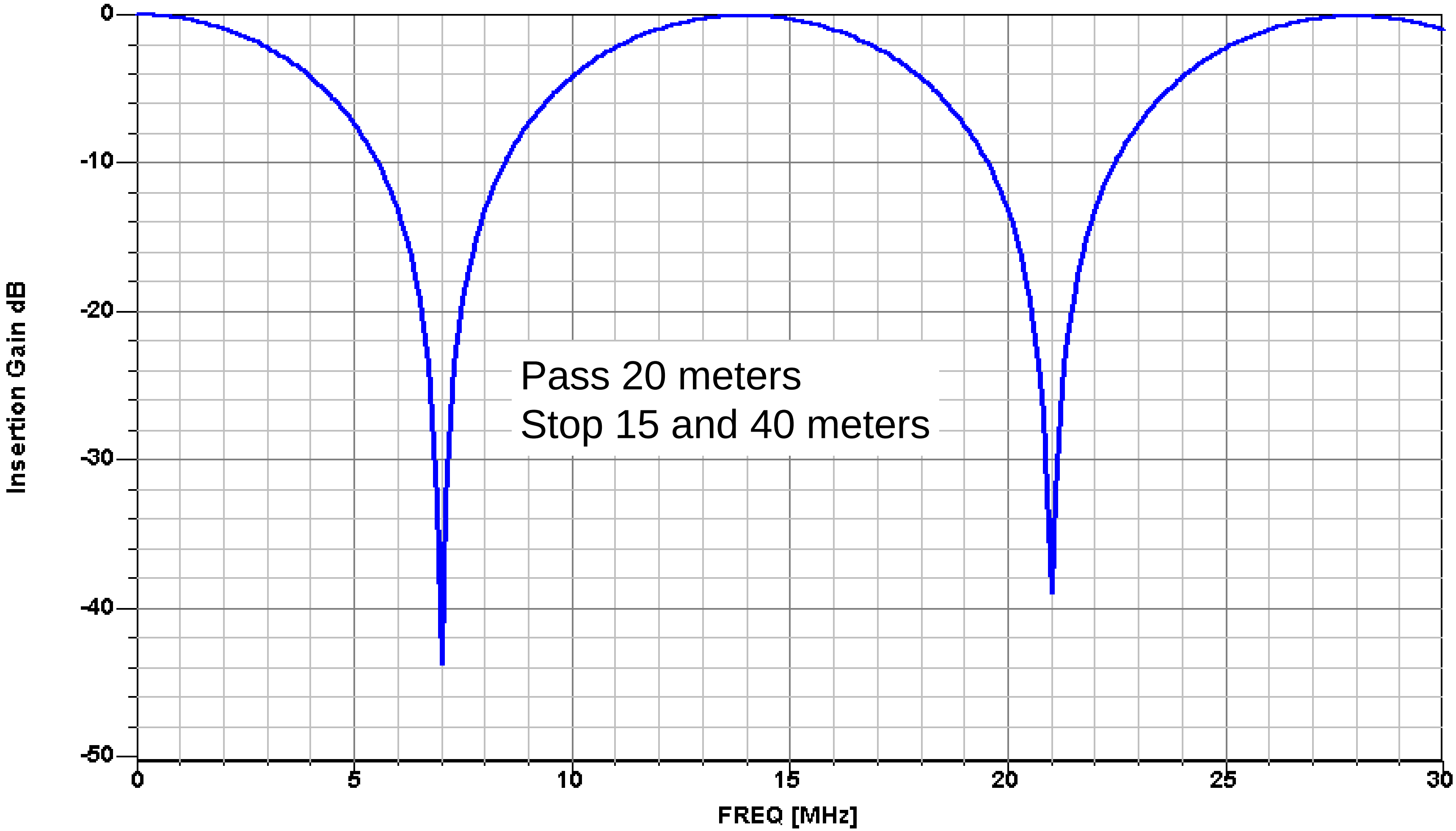
Single Shunt Stub Filter, Quarter-Wave at 1 MHz



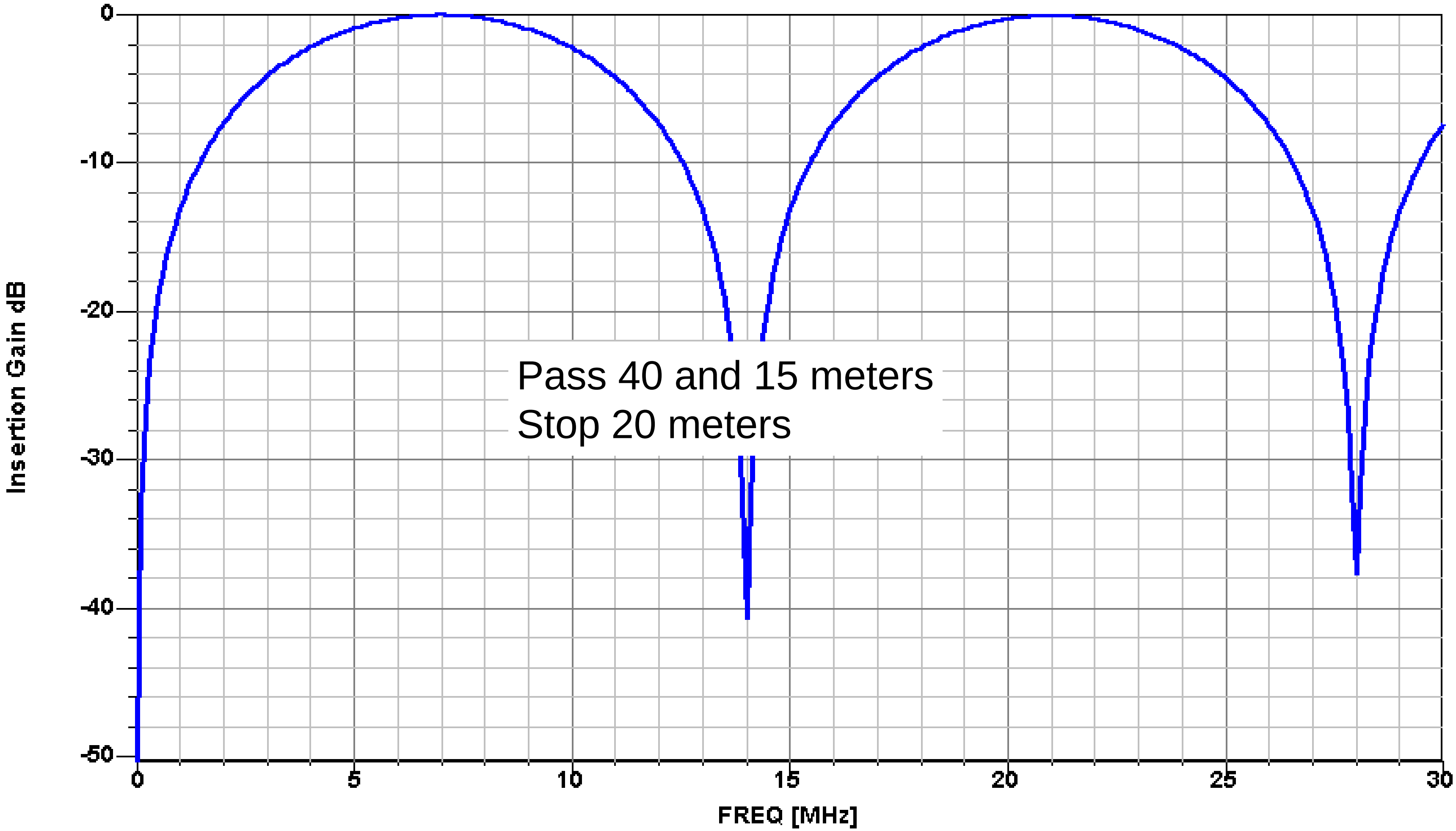
Many Amateur HF Bands are Harmonically Related



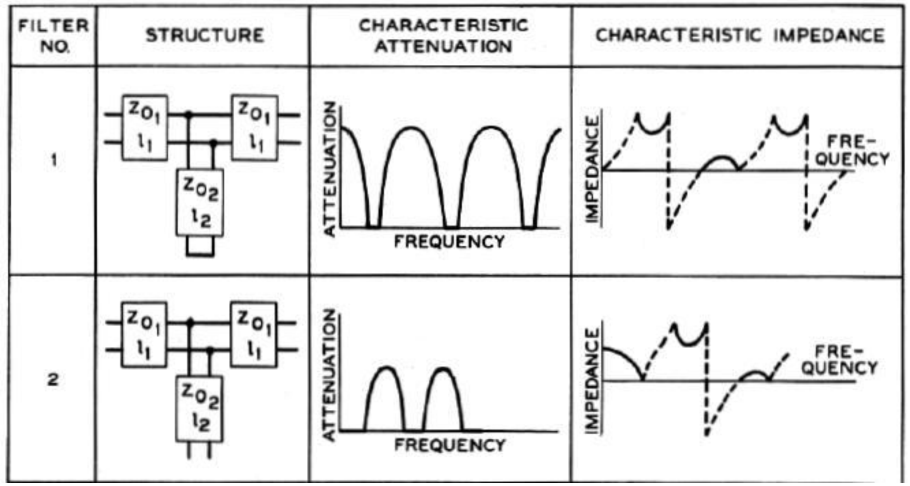
Example 1 of Single Open-Circuited Stub Filter

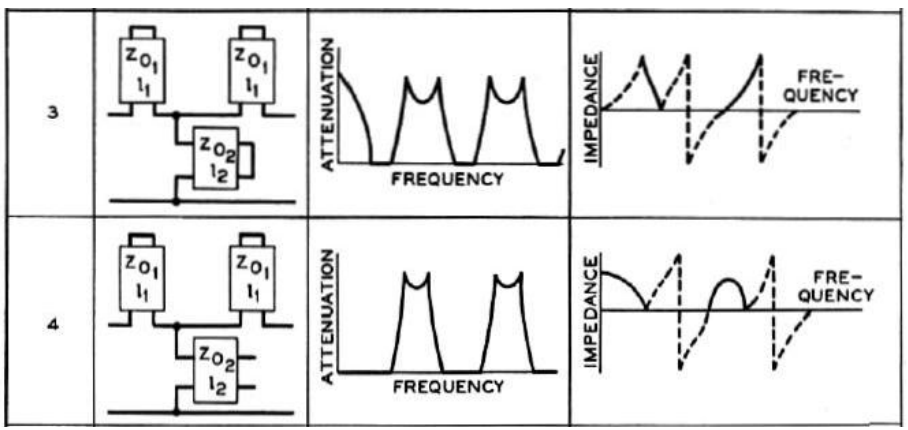


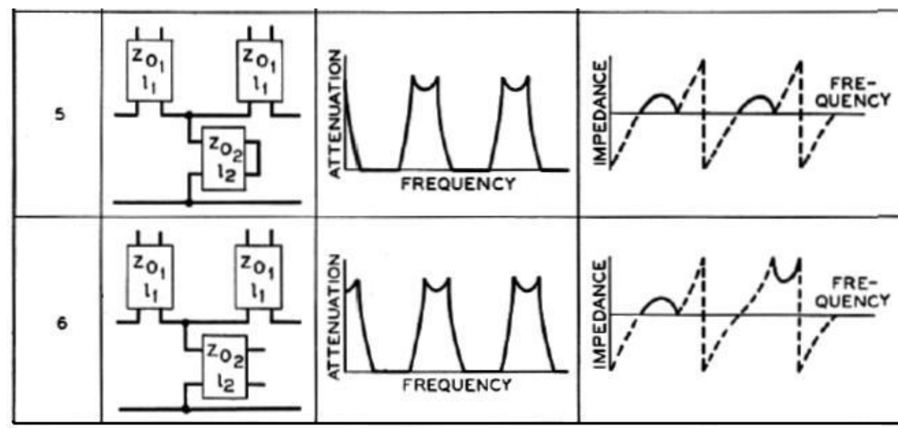
Example 2 of Single Short-Circuited Stub Filter



Simple Transmission Line Filters







W.P. Mason and R.A. Sykes, *Bell Syst. Tech. J.*, July 1937

Warren Perry Mason, 1900-1986

Courtesy of AT&T Archives and History Center

Filters with Multiple Pass and Stop Frequencies

- **Suppose we are given a set of discrete frequencies in ascending order**

$$f_1 < f_2 < \cdots < f_{N-1} < f_N$$

- **Each frequency is designated as either pass or stop**
- **Consider the case of three frequencies**
- **We focus on the non-trivial cases**
  - 2 pass and 1 stop frequency
  - 2 stop and 1 pass frequency

f_1	f_2	f_3
Pass	Pass	Pass
Pass	Pass	Stop
Pass	Stop	Pass
Pass	Stop	Stop
Stop	Pass	Pass
Stop	Pass	Stop
Stop	Stop	Pass
Stop	Stop	Stop

Design Synthesis Procedure for Reflection Stub Filter

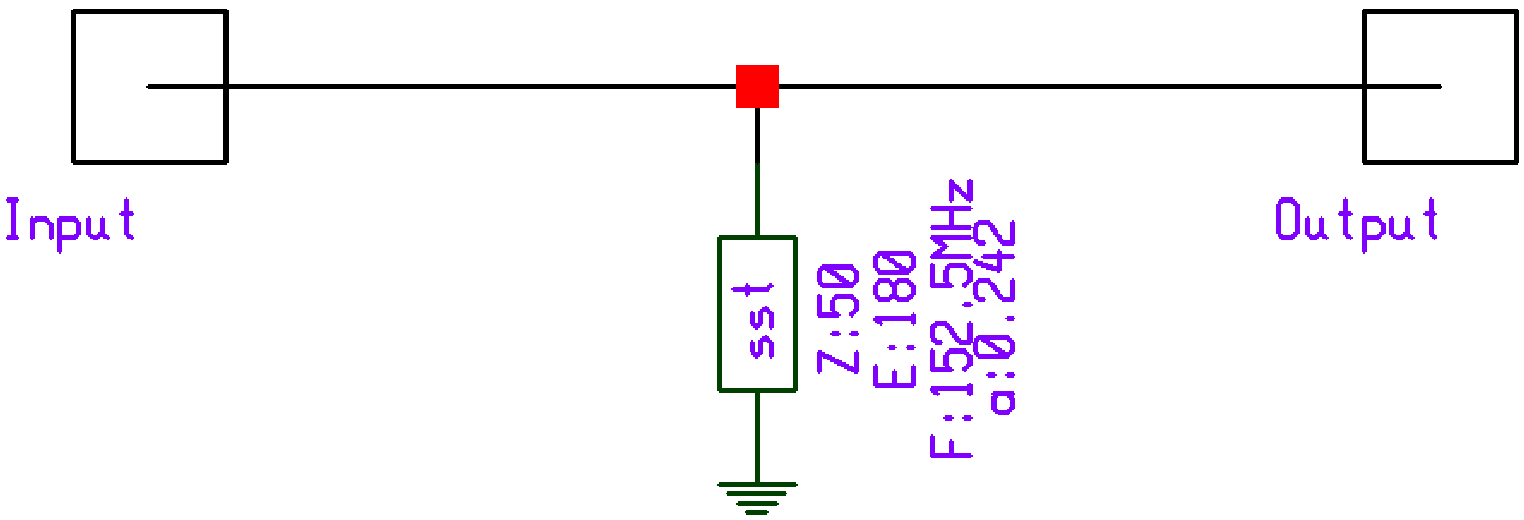
- **Decide 1 or 2 pass frequencies and 1 or 2 stop frequencies**
- **Decide port impedances – antenna or 50 ohms**
- **Synthesis procedure for ladder network:**
- **Step 1**
  - Insert quarter wave open stubs or half-wave shorted stubs for each stop frequency, stubs all in shunt
- **Step 2 (on Smith chart)**
  - For 1 pass frequency, insert transmission line section and adjust Z_0 and length to revolve the impedance point of the pass frequency to center
  - For 2 pass frequencies, insert transmission line section and adjust Z_0 and length to revolve the impedance points of both pass frequencies to the unit conductance circle, i.e. $g = 0$
- **Step 3 (for 2 pass frequencies)**
  - If the upper pass frequency point is above (counter-clockwise) from the lower pass frequency point, insert a shunt open stub and adjust length to bring both points to center
  - If the upper pass frequency point is below (clockwise) from the lower pass frequency point, insert a shunt shorted stub and adjust length to bring both points to center
- **Final step – fine tune design**
  - Run optimizer on all adjustable parameters to dial in design goals (bandwidths, insertion loss, SWR) and satisfy design constraints (allowed Z_0 values)

Pager Rejection Filter

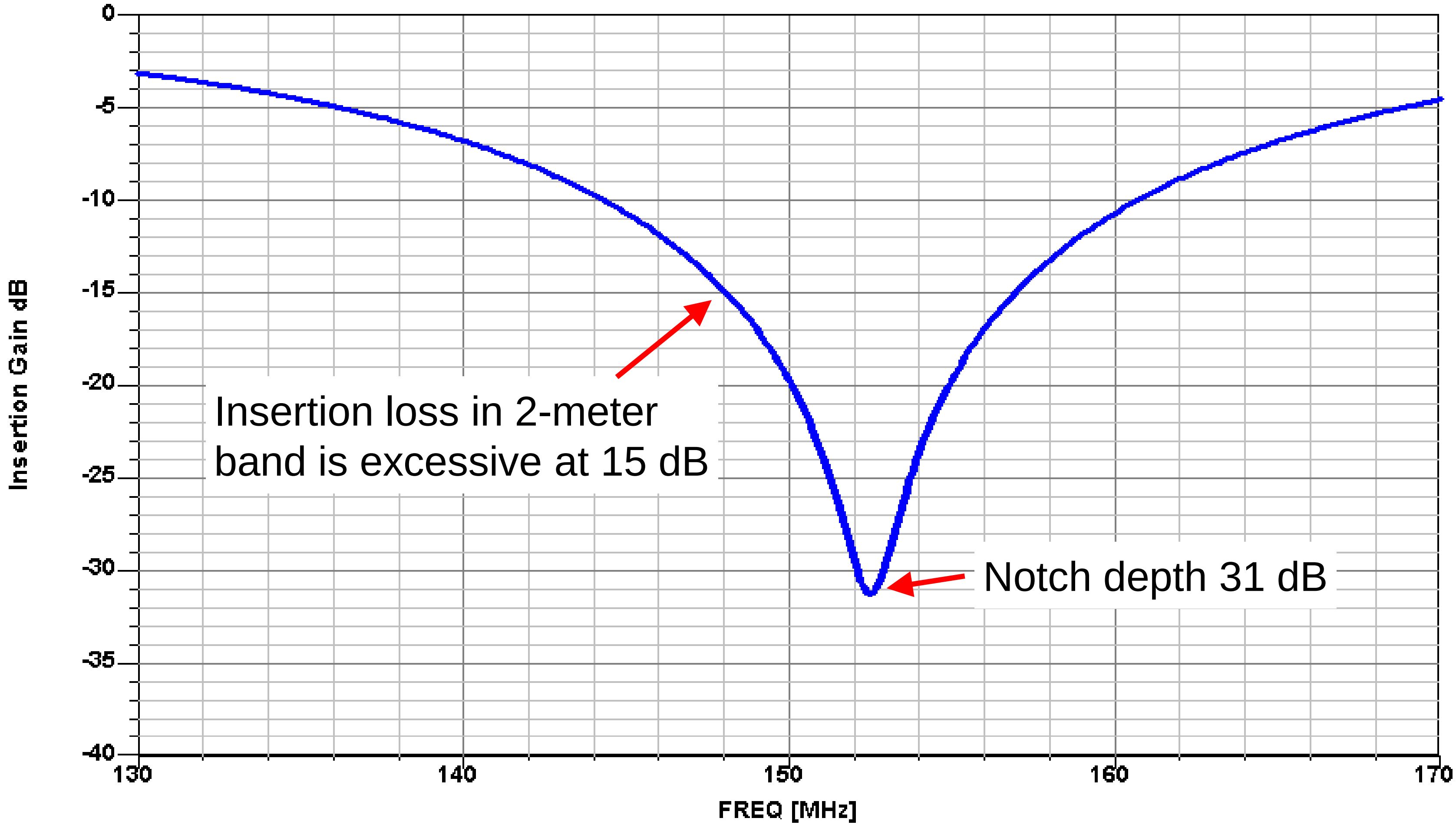
K6OIK

ARRL Pacificon 2002

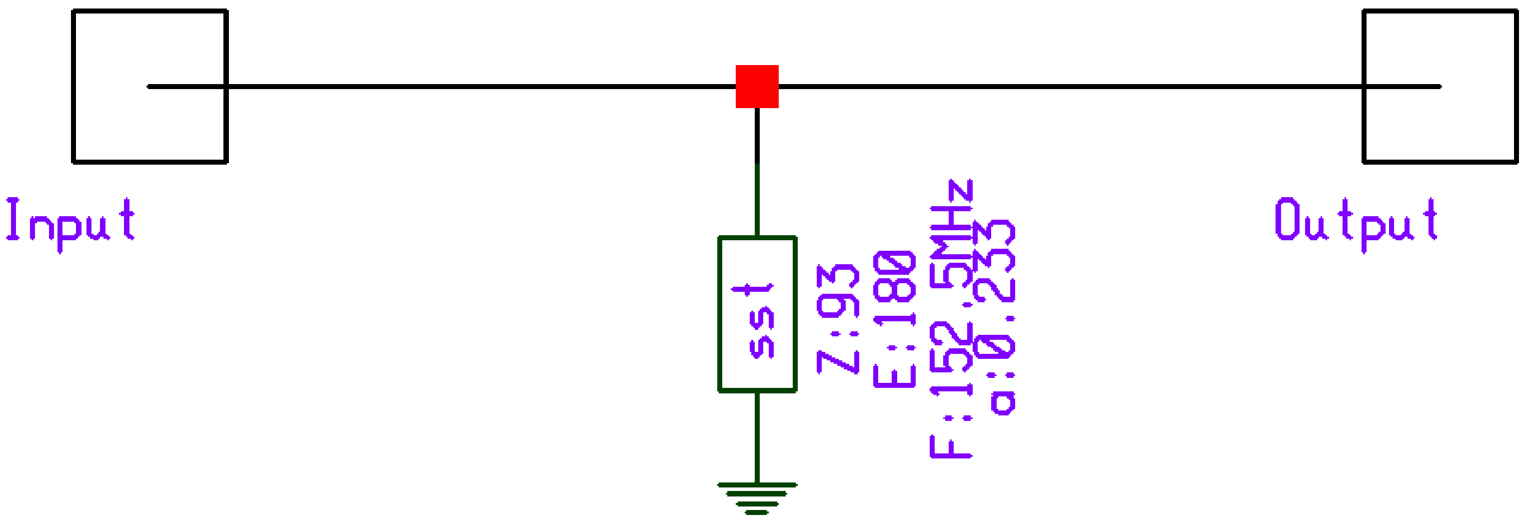
First Attempt: The Classic Trap Filter
Half-Wavelength Shorted Stub in Shunt



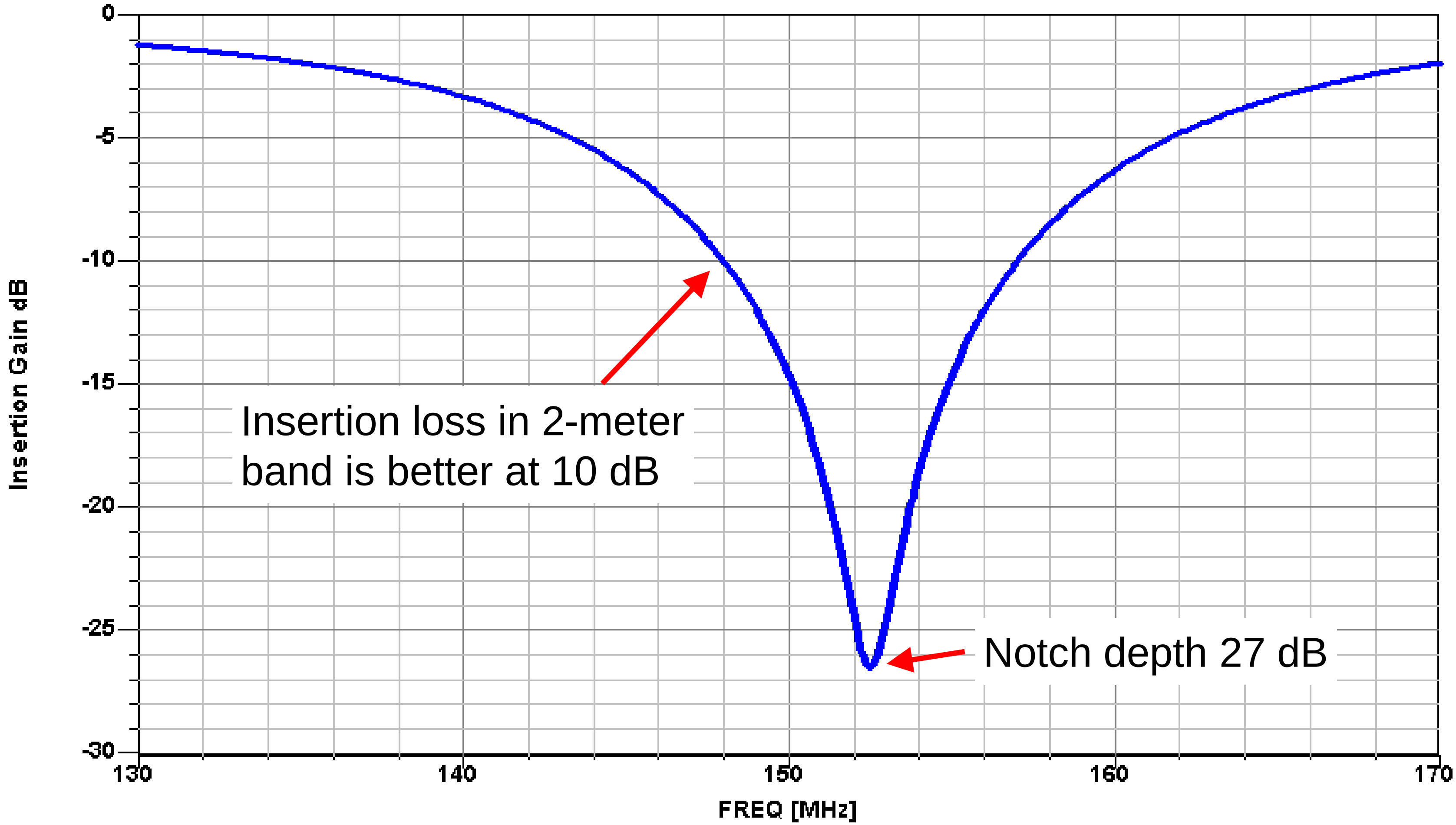
Good Notch Depth
But High Insertion Loss in 2-Meter Band!



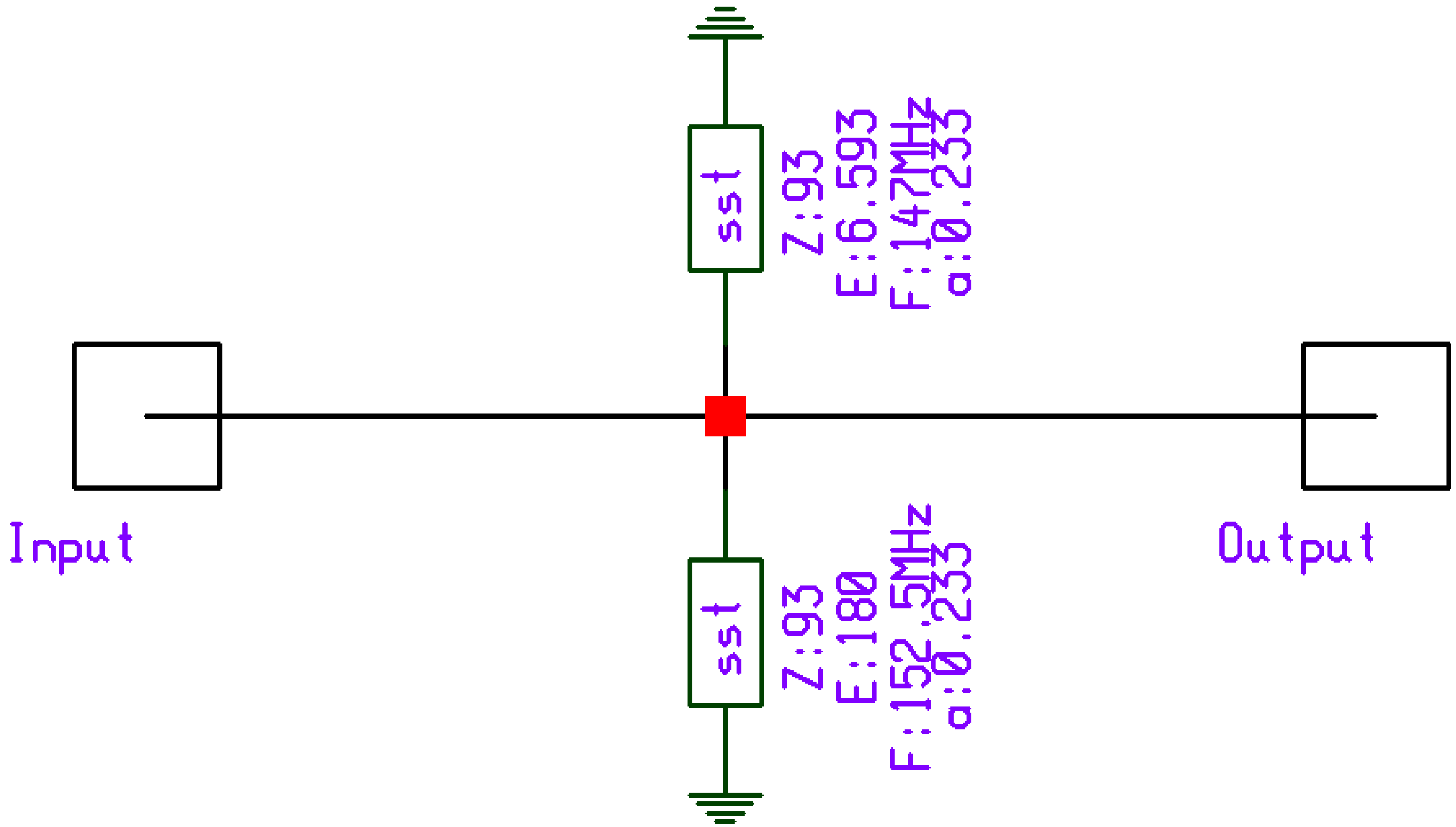
First Modification
Change Stub to RG62 High-Impedance Coax



Reduced Insertion Loss in 2-Meter Band
But More Improvement Needed!



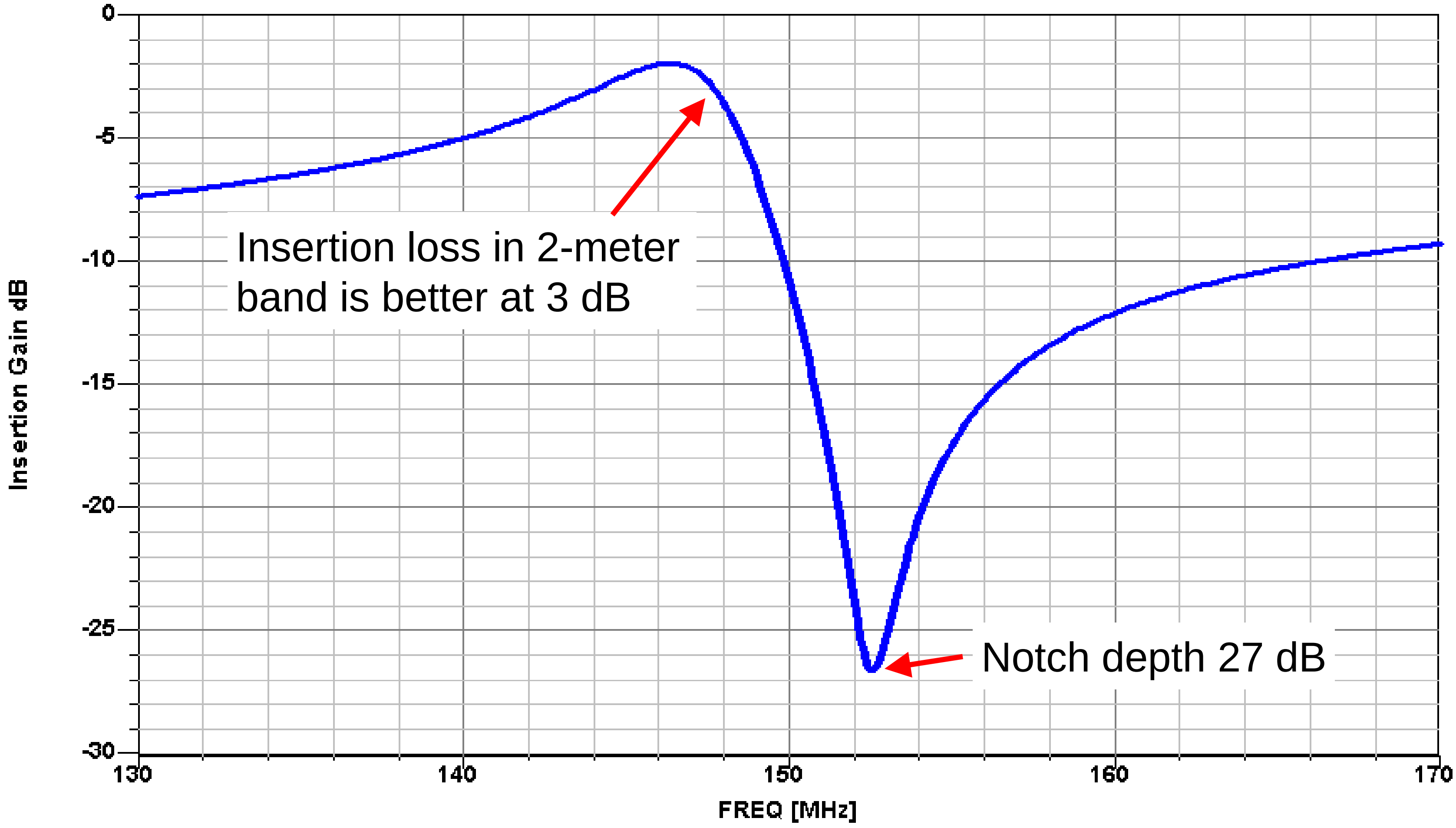
Second Modification
Second Stub Peaks 2-Meter Response via Inductance



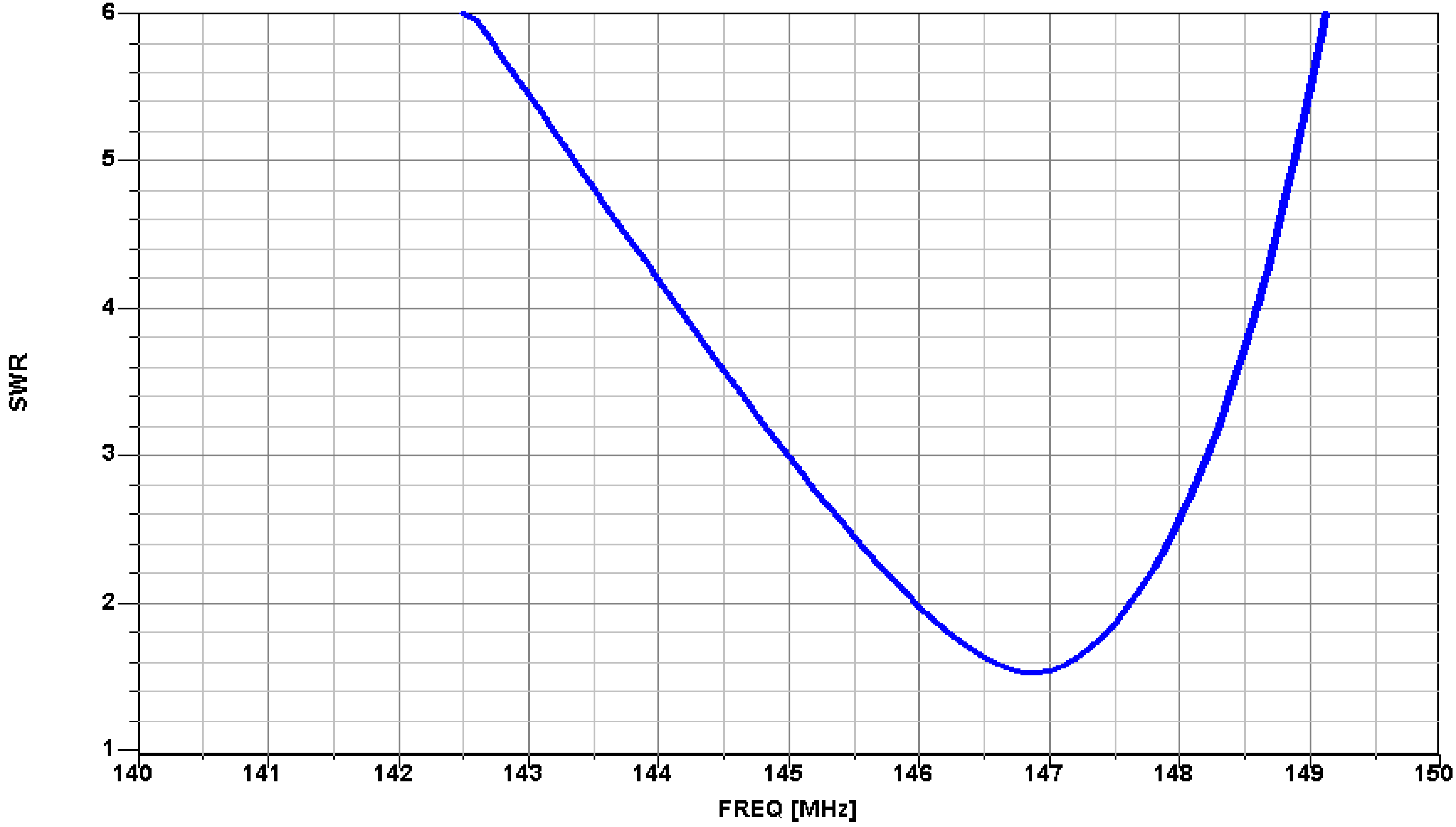
How It Works

- **Notch frequency is above pass frequency**
- **Primary rejection stub acts like**
  - Series resonant circuit at the notch frequency
  - Shunt capacitor at the pass frequency
- **Second stub in parallel with primary stub acts like**
  - Inductor at the pass frequency
- **Together the stubs act like a parallel resonant circuit at the pass frequency, i.e. high shunt impedance**
- **Notch depth and insertion loss at pass frequency are limited only by line losses of stubs**
- **Use of low-loss line gives:**
  - Deeper null at notch frequency
  - Smaller insertion loss at pass frequency

Frequency Response of Two-Stub Filter

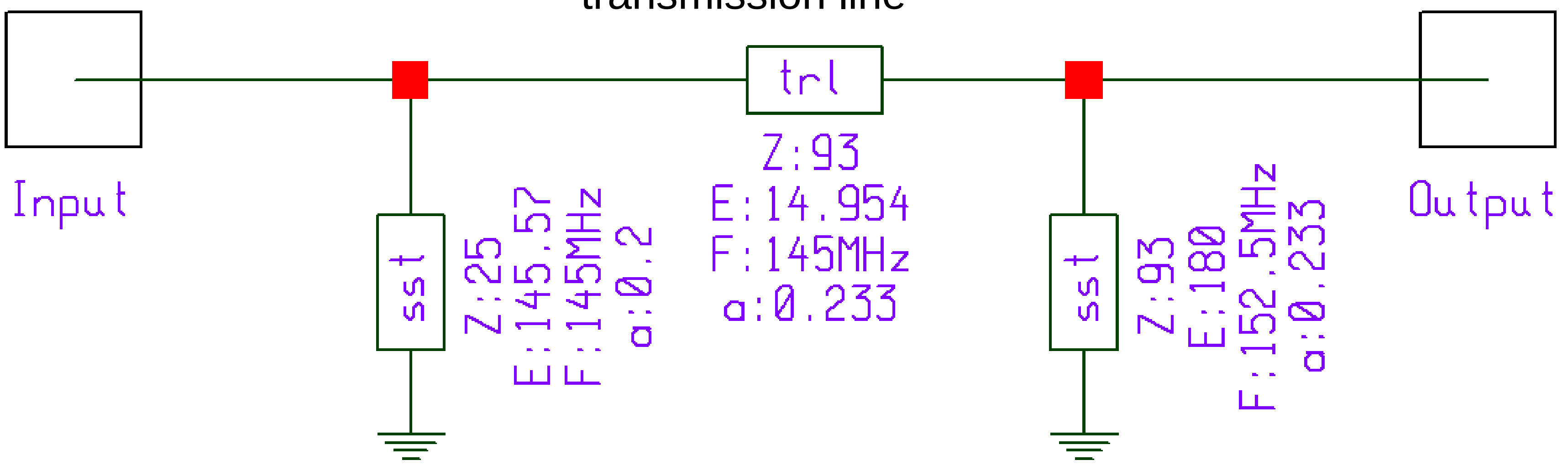


Input SWR of Two-Stub Filter



Third Modification – Transmission Line between Stubs Gives LPF Response

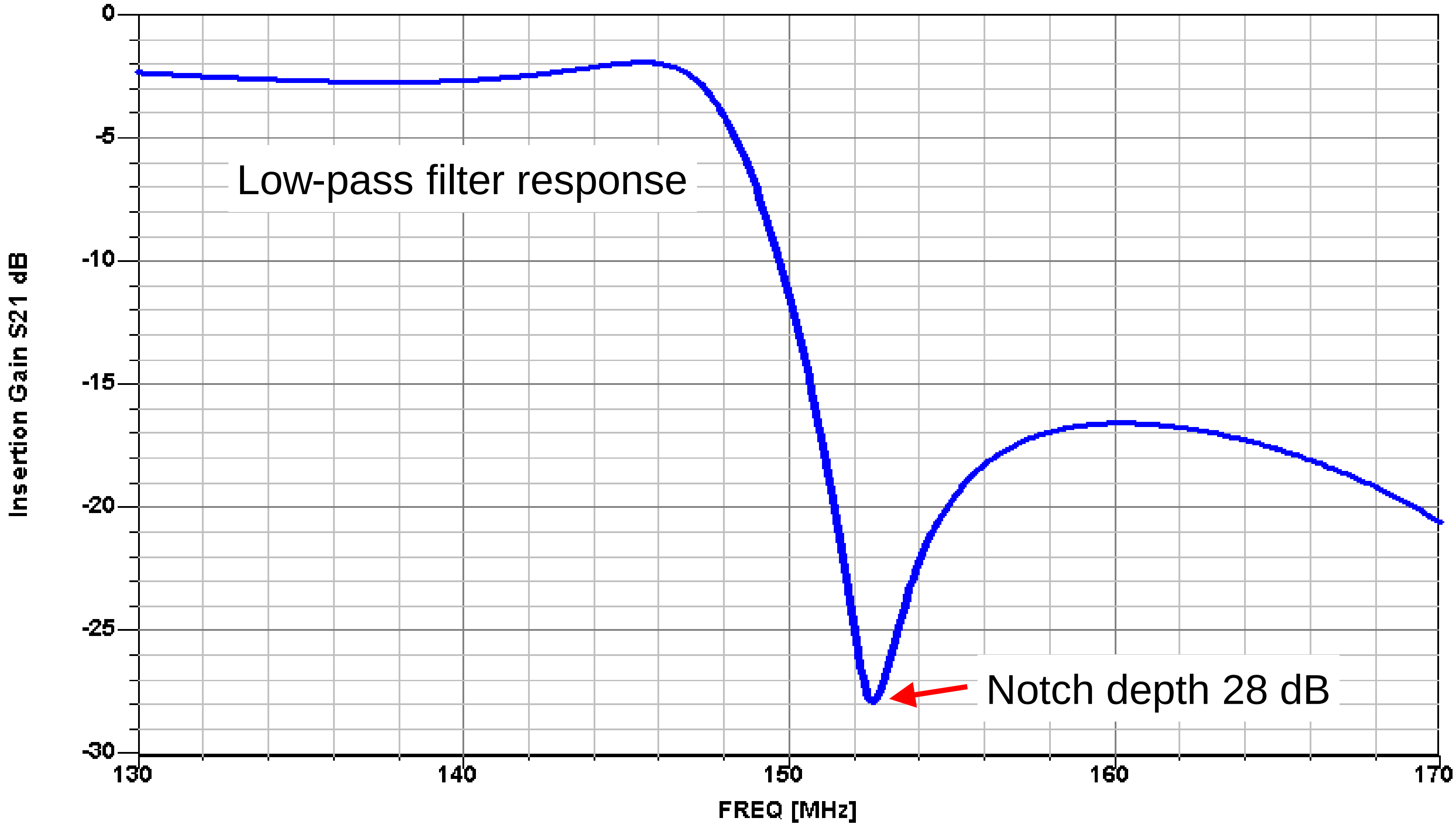
Segment of 93-ohm transmission line



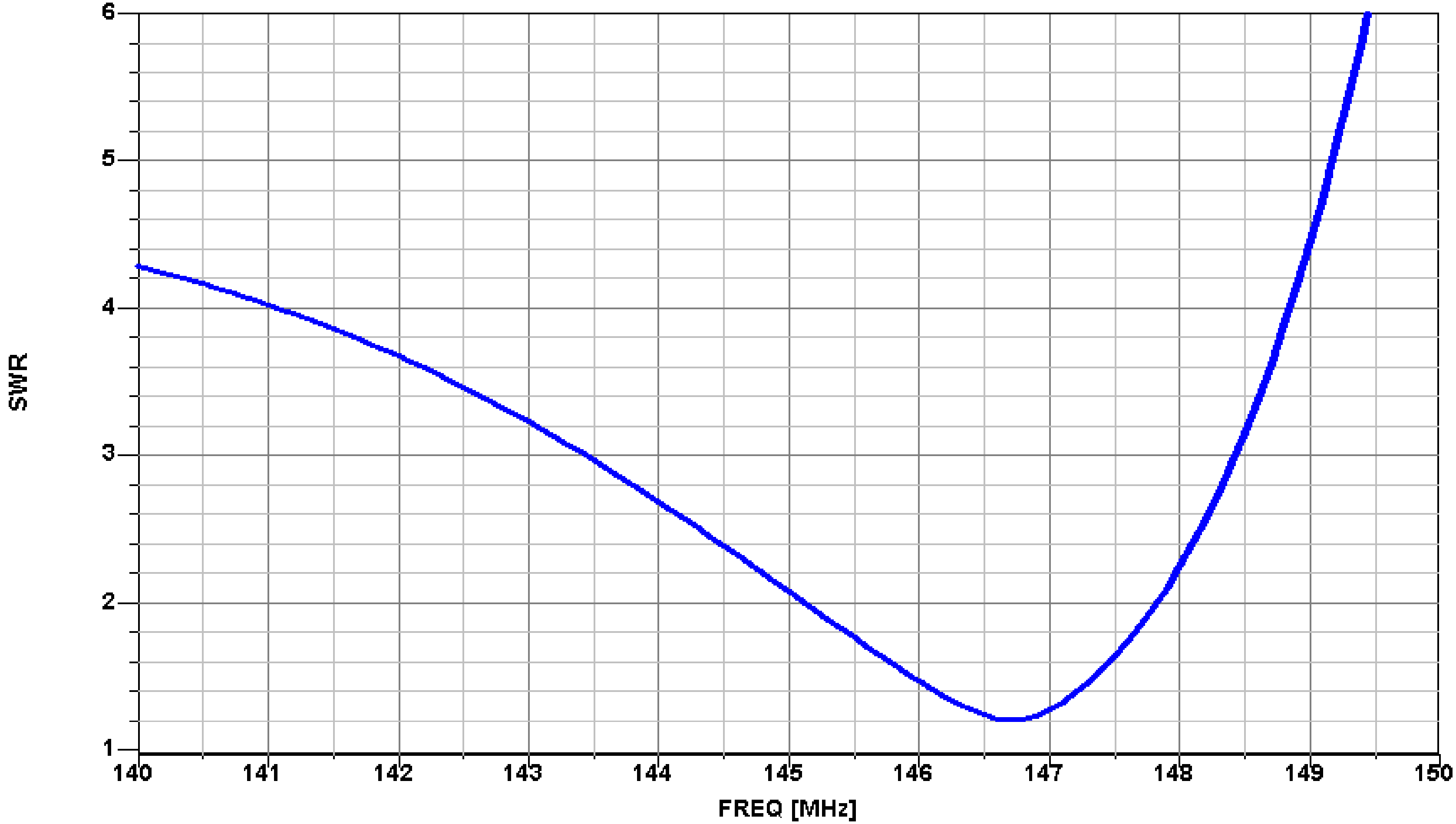
25-ohm short-circuited stub

93-ohm short-circuited stub

Low-Pass Filter with a Rejection Notch

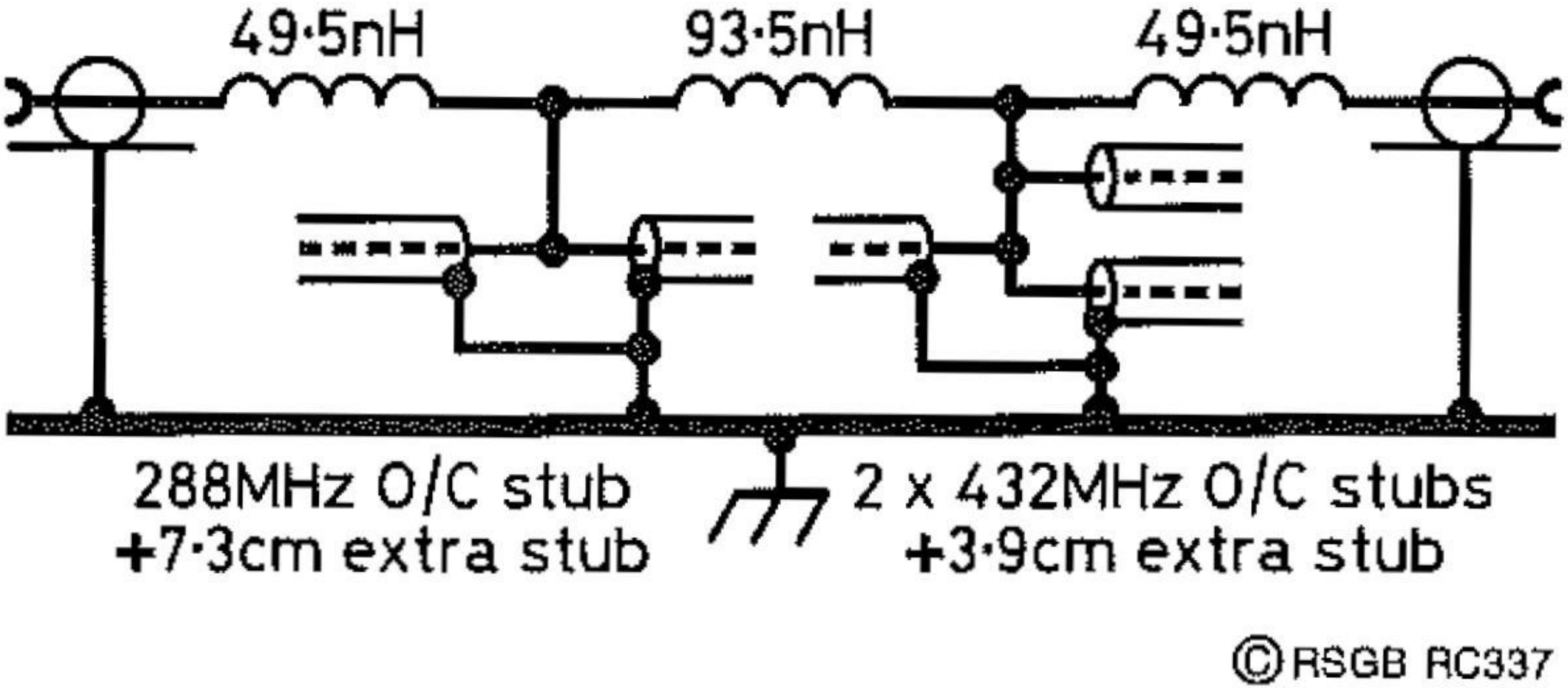


Input SWR of Improved 2-Stub Filter



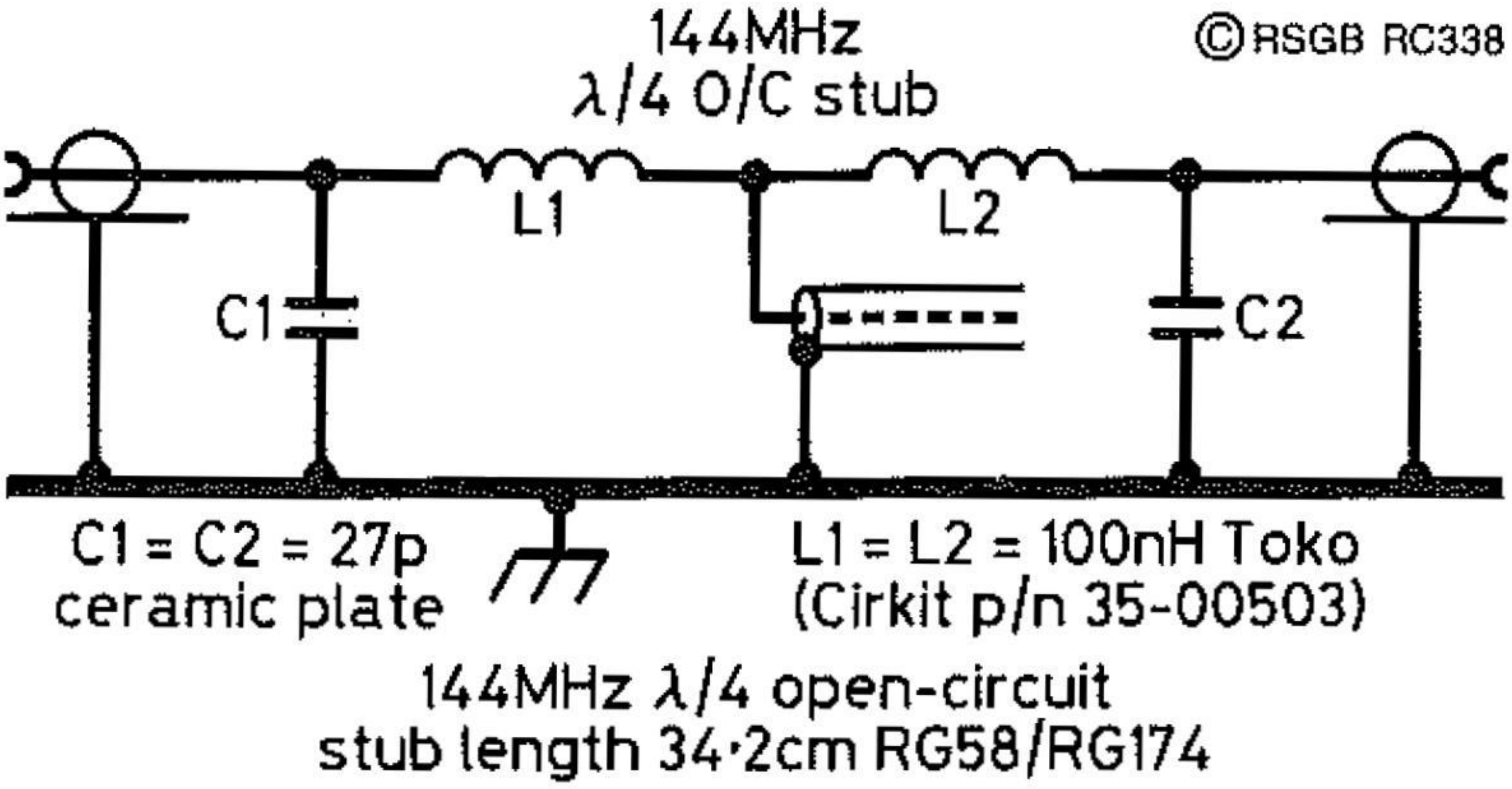
Hybrid Filters Using Lumped Elements and Stubs

DL1GBH 2-Meter Harmonic Filter



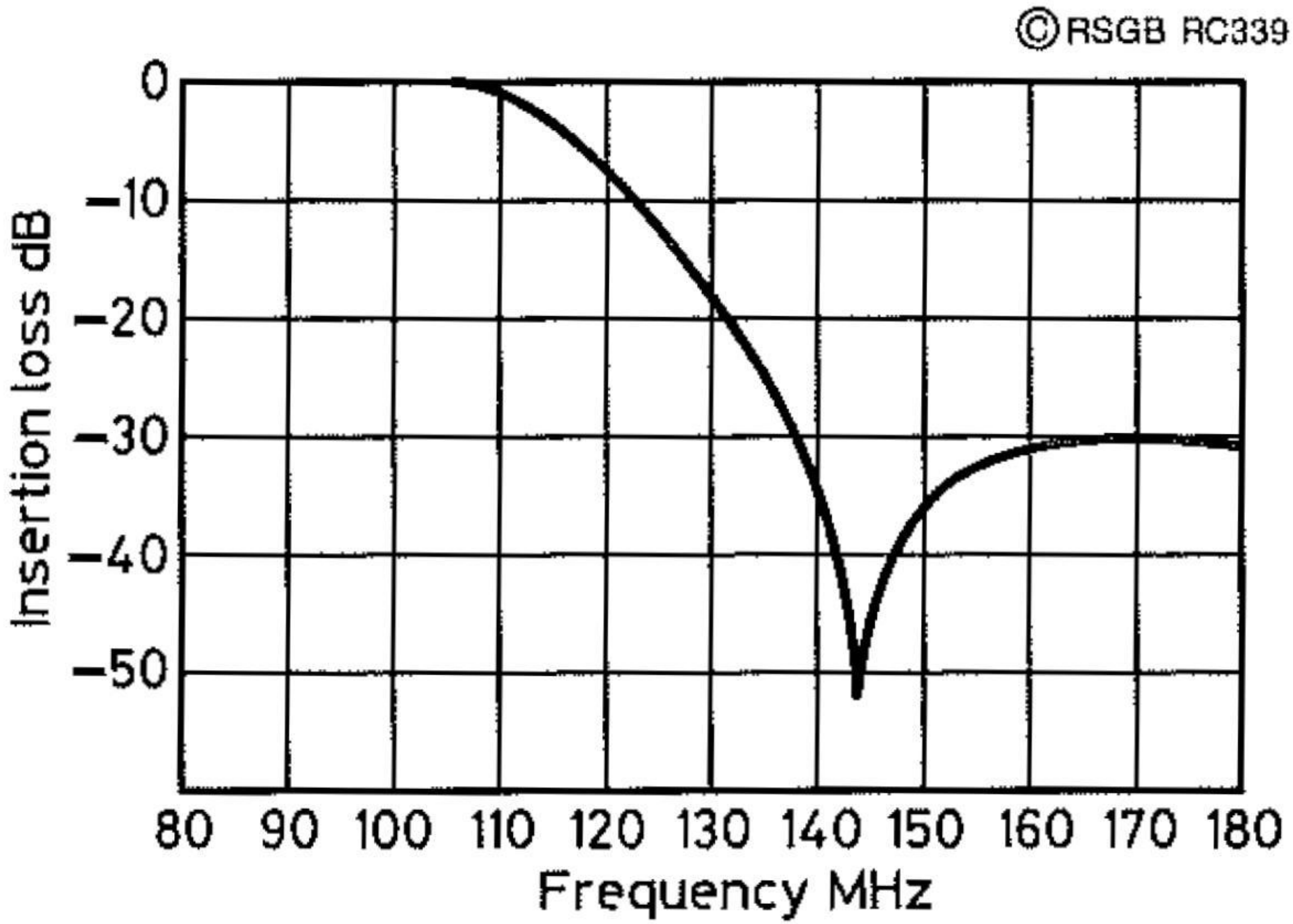
J. Regnault, G4SWX, *RadCom* (RSGB), Nov. 1994

G4SWX FM Broadcast Pass, 2-Meter Reject Filter



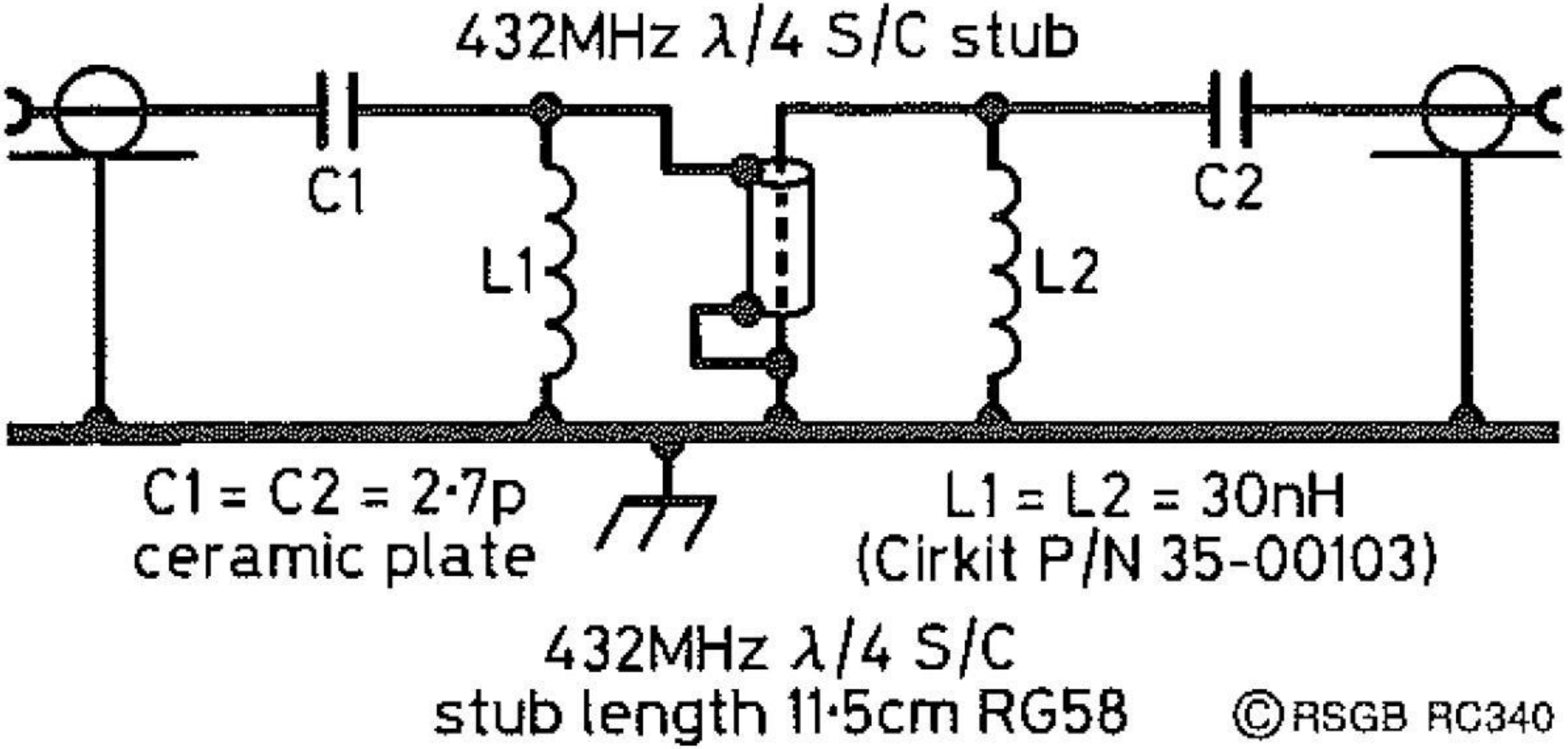
J. Regnault, G4SWX, *RadCom* (RSGB), Nov. 1994

FM Broadcast, 2-Meter Reject Filter Performance



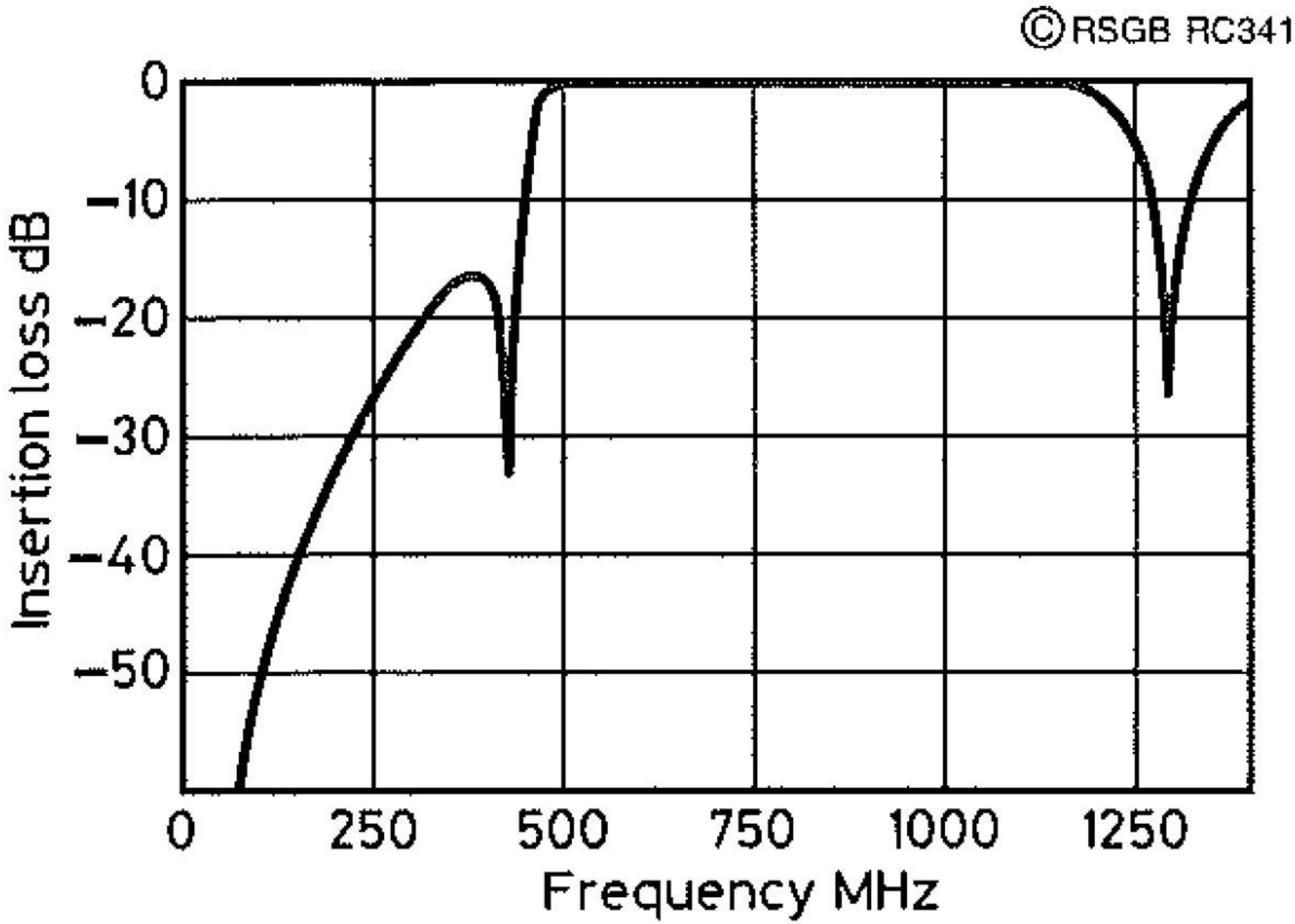
G4SWX UHF TV Pass, 432 and 1296 MHz Reject Filter

Series Stub

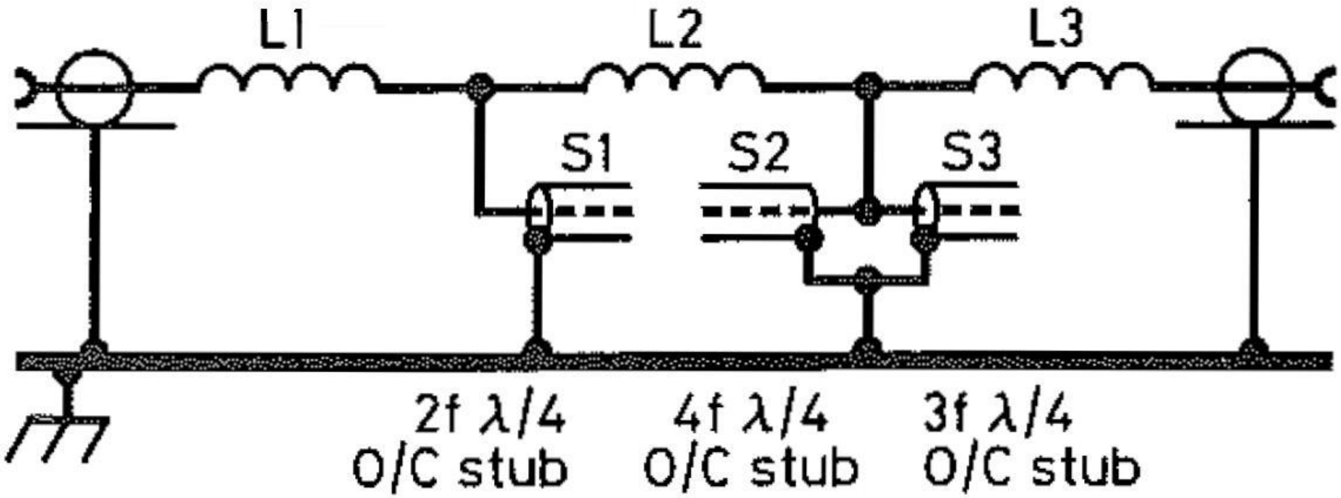


J. Regnault, G4SWX, *RadCom* (RSGB), Nov. 1994

UHF TV Filter Performance



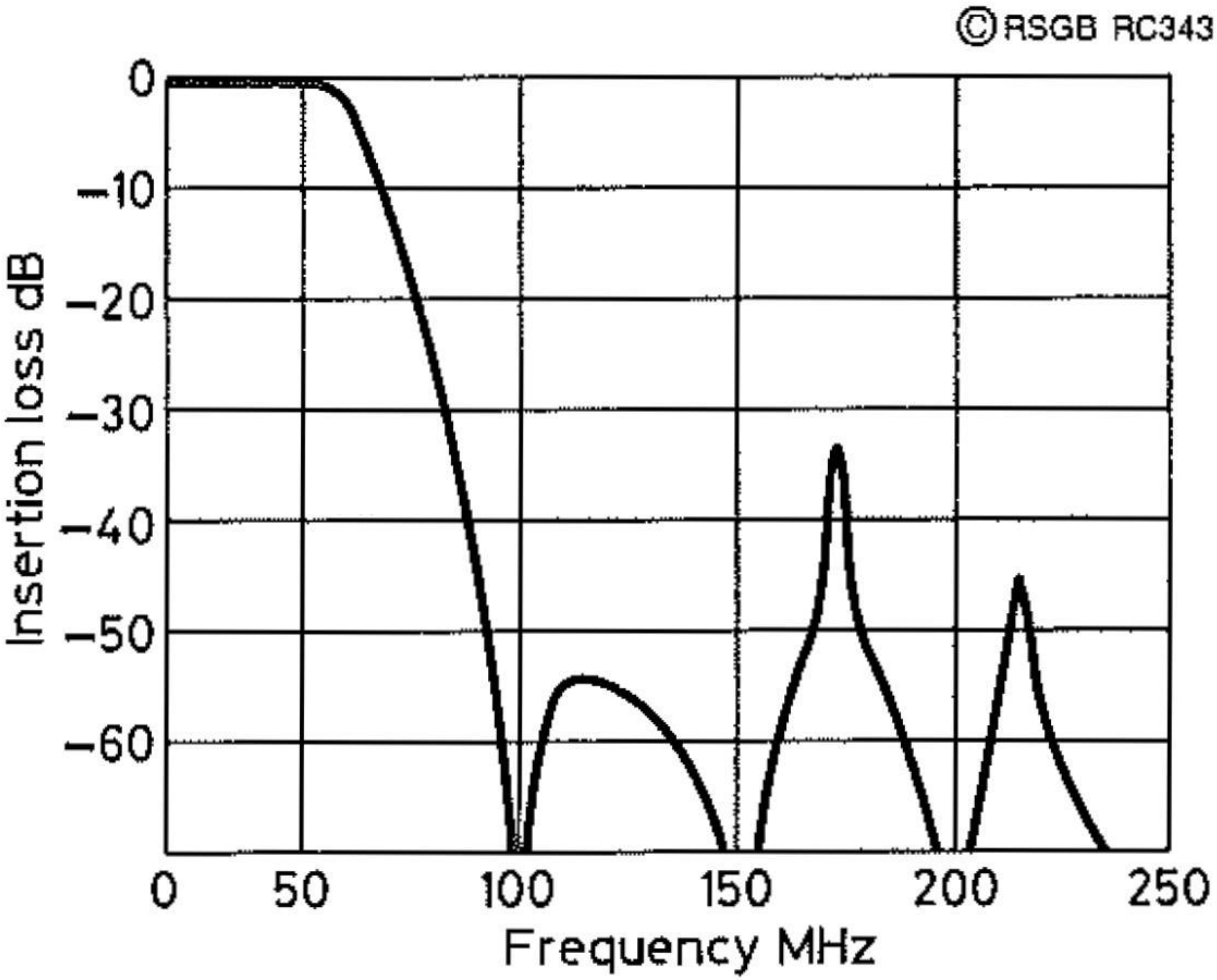
G4SWX Tx Low Pass Filters for 50 & 144 MHz Bands



	50MHz	144MHz	
L1 = L3	175nH	60nH	
L2	340nH	115nH	
S1	48·9cm	17·2cm	all stubs
S2	24·7cm	8·6cm	UR43/
S3	32·7cm	11·5cm	RG58 coax

J. Regnault, G4SWX, *RadCom* (RSGB), Nov. 1994

50 MHz Tx Low Pass Filter Performance

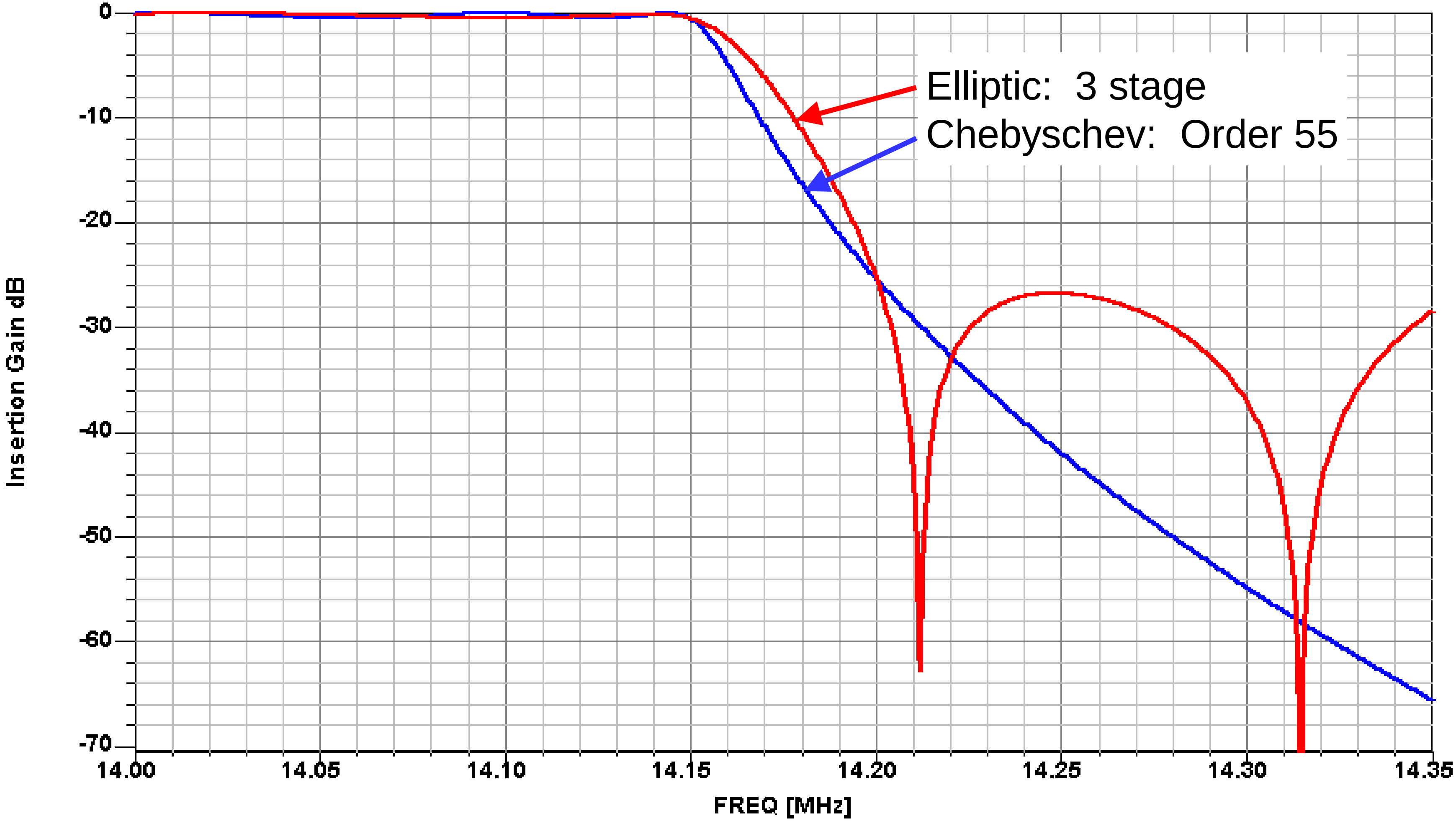


Sub-Band Filters for Field Day

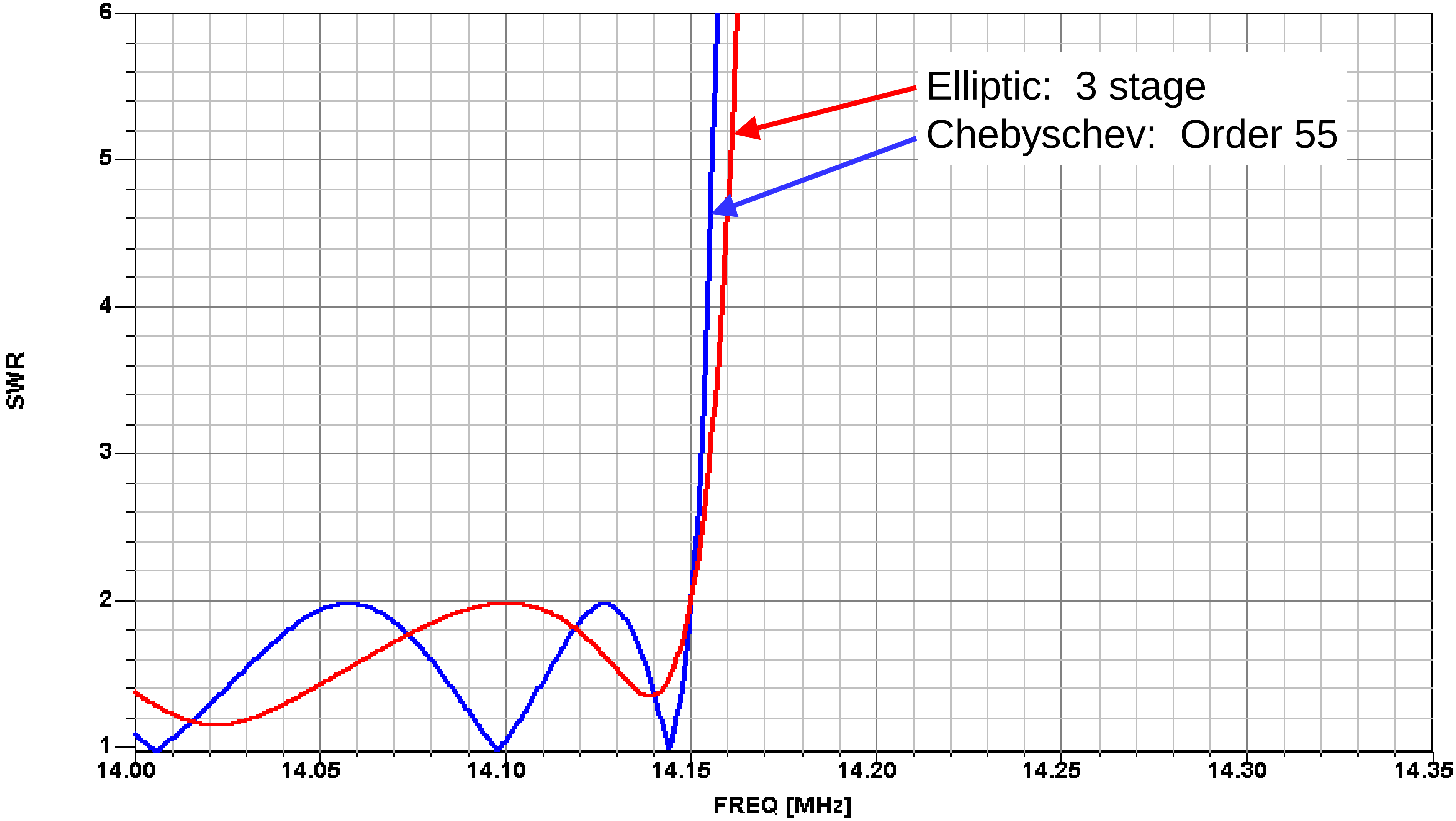
Sub-Bands to be Isolated by Filtering

Band (meters)	CW / Digital Sub-band	Phone Sub-band	Transition Skirt Width
10	28.000 – 28.150	28.300 – 28.500	0.53%
15	21.000 – 21.100	21.200 – 21.450	0.47%
☞ 20	14.000 – 14.150	14.200 – 14.350	1.06%
40	7.000 – 7.100	7.150 – 7.300	0.70%
80	3.000 – 3.600	3.700 – 4.000	2.74%

Comparison of Lumped-Element Prototype Filters

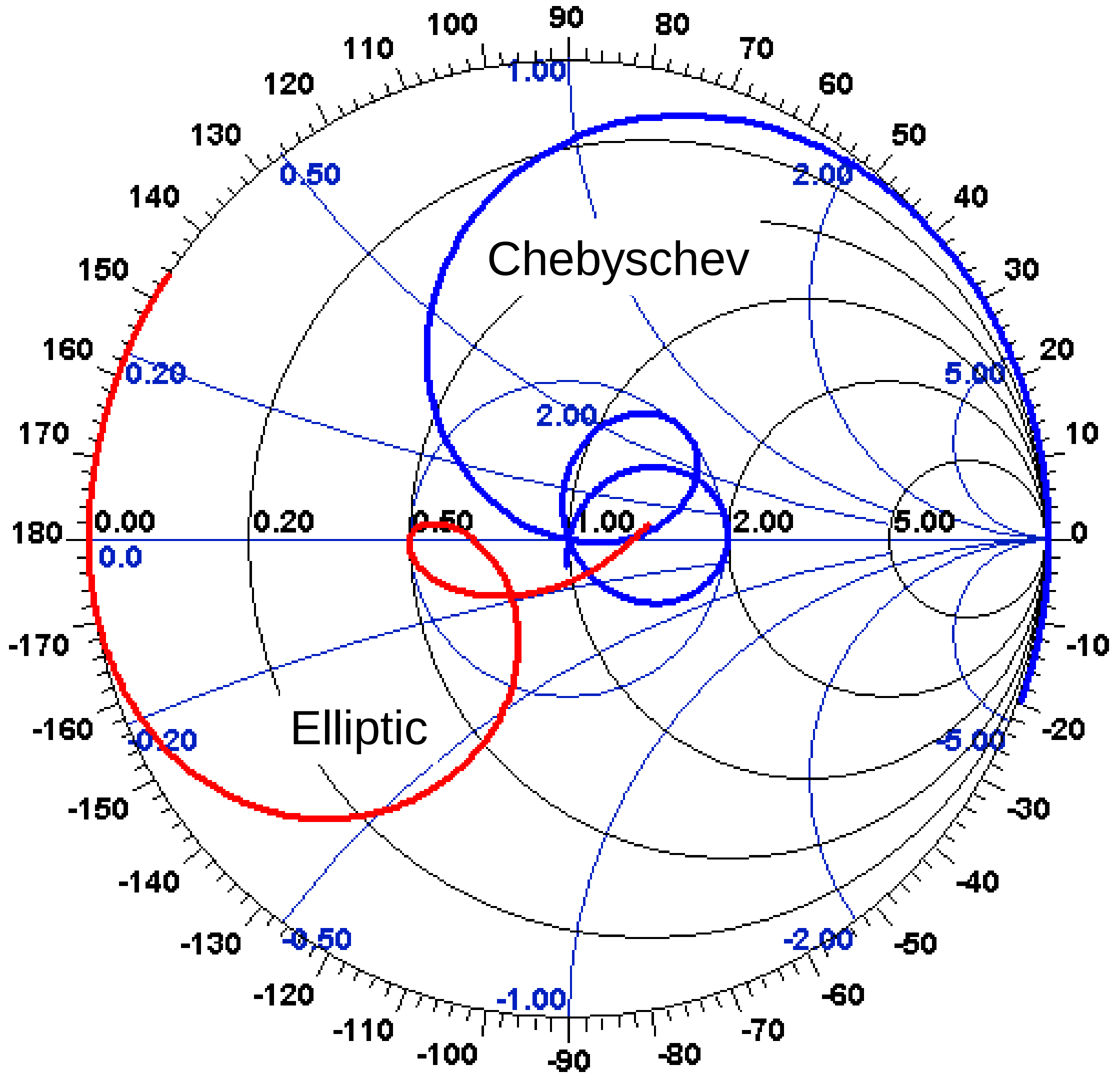


Input SWR

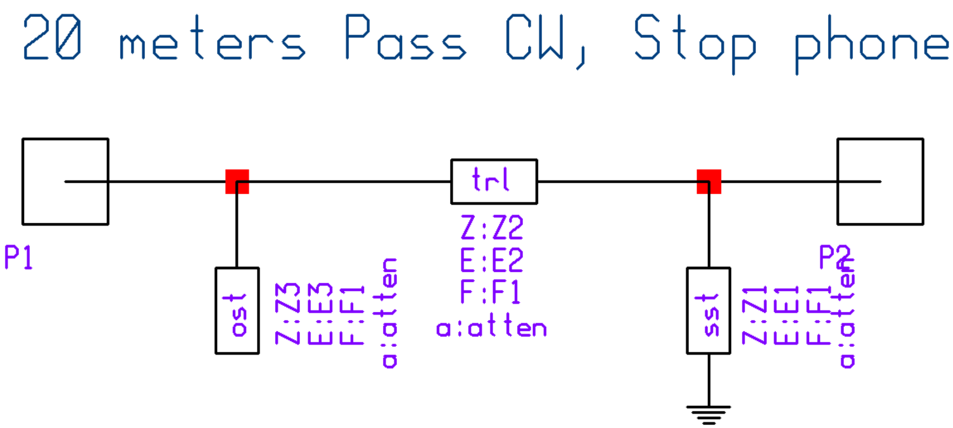


6
5
4
3
2
1
SWR
14.00
14.05
14.10
14.15
14.20
14.25
14.30
14.35
FREQ [MHz]
Elliptic: 3 stage
Chebyschev: Order 55

Filter Input Impedance on Smith Chart



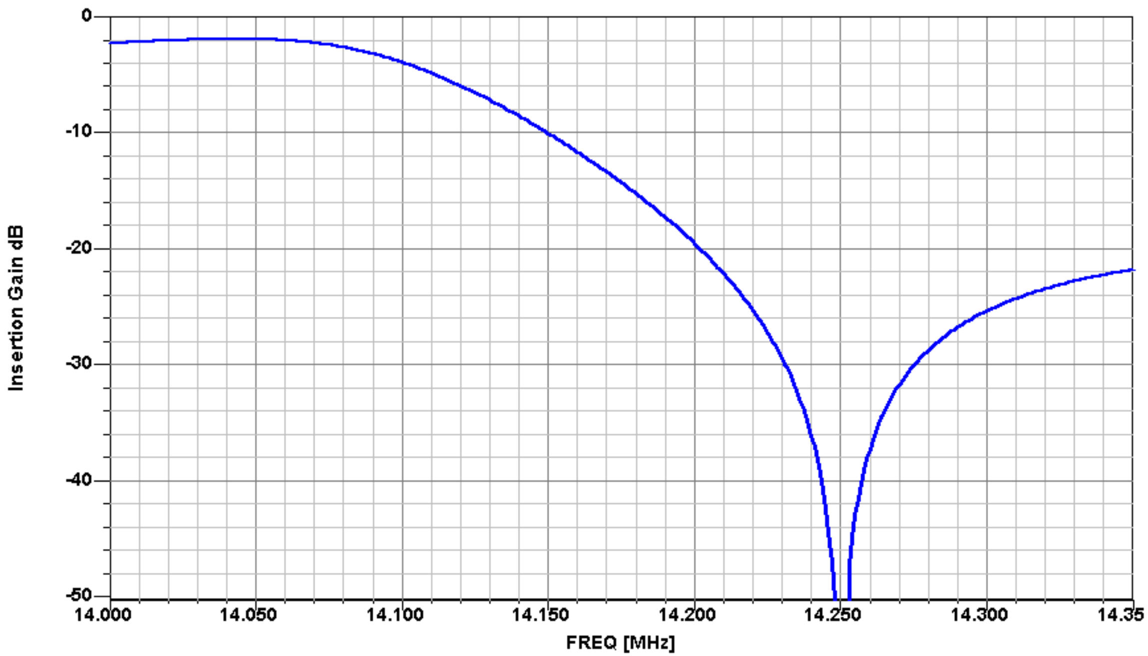
Example 1: 2-Stub Filter Optimized by Serenade SV



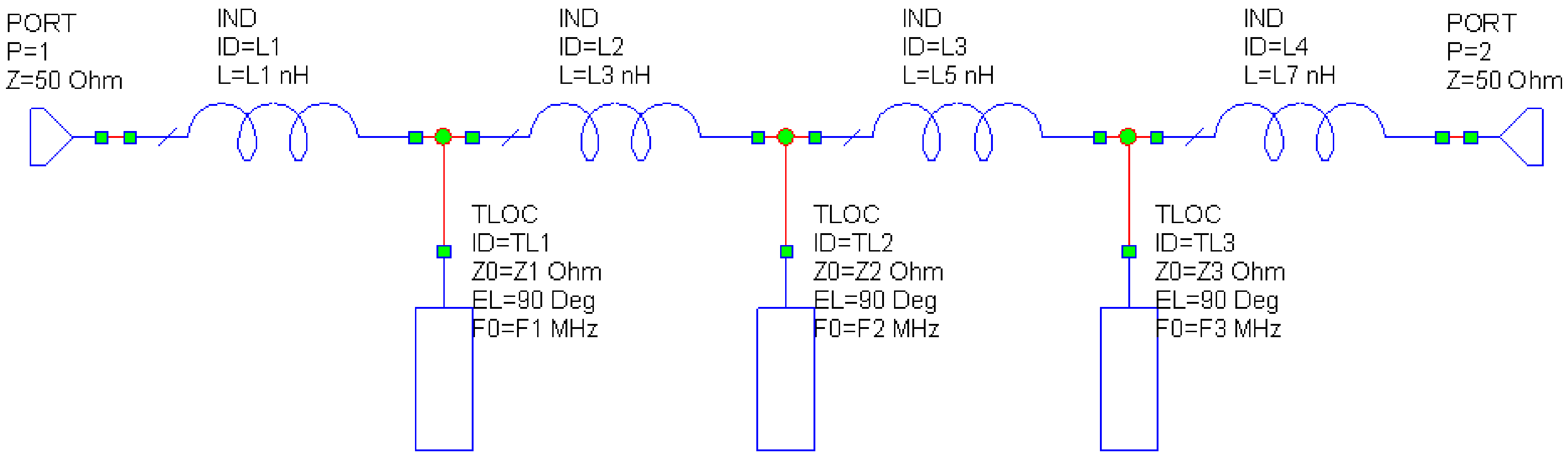
E1 = 180 deg
E2 = 18.5 deg
E3 = 86.3 deg

} *f* = 14.250 MHz

Z1 = 500 Ω
Z2 = 98 Ω
Z3 = 125 Ω
atten = 0



Example 2: 3-Stub Filter Found by Microwave Office



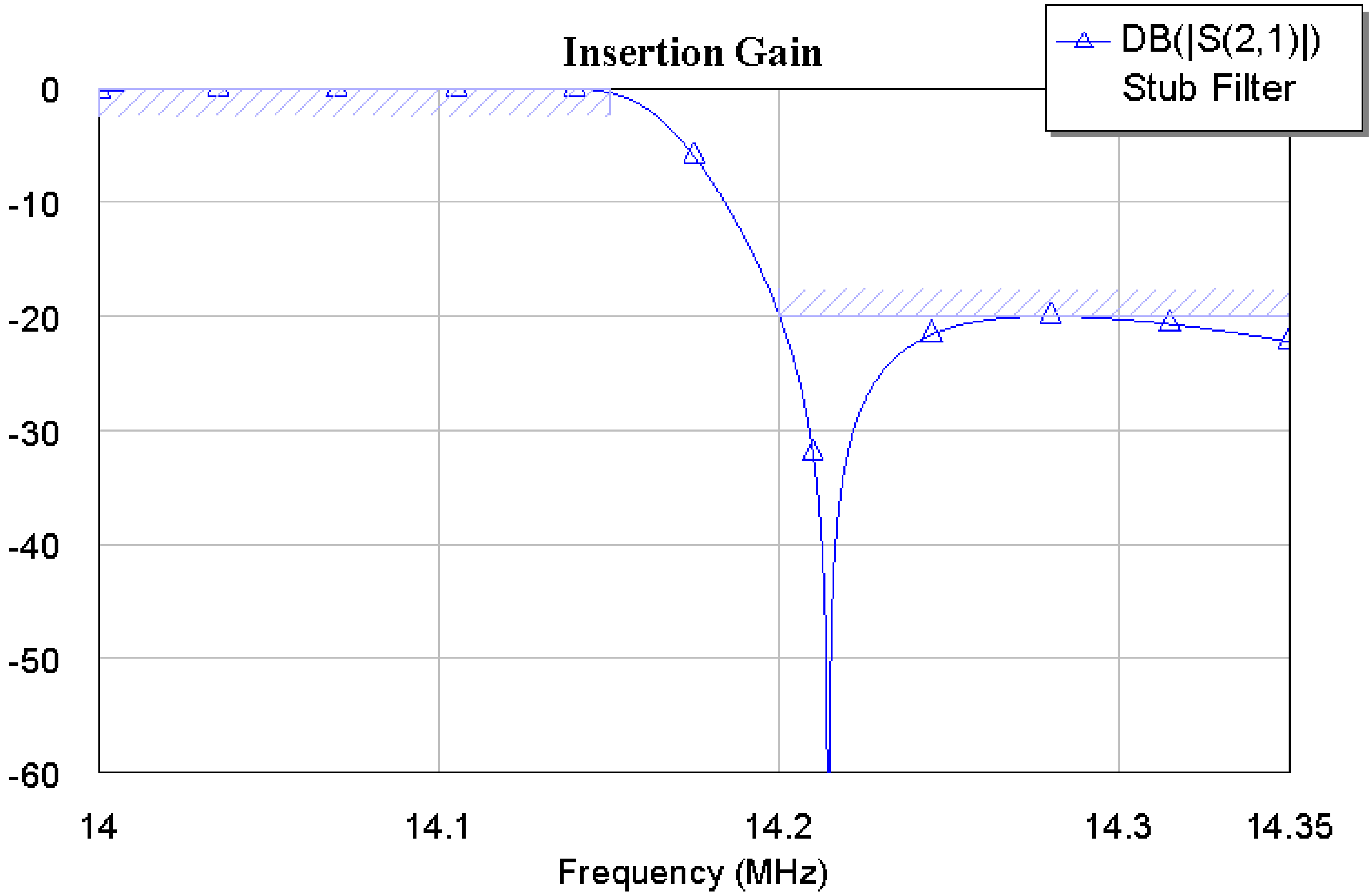
F1 = 14.6 MHz
Z1 = 199.6 Ω

F2 = 14.21 MHz
Z2 = 199.2 Ω

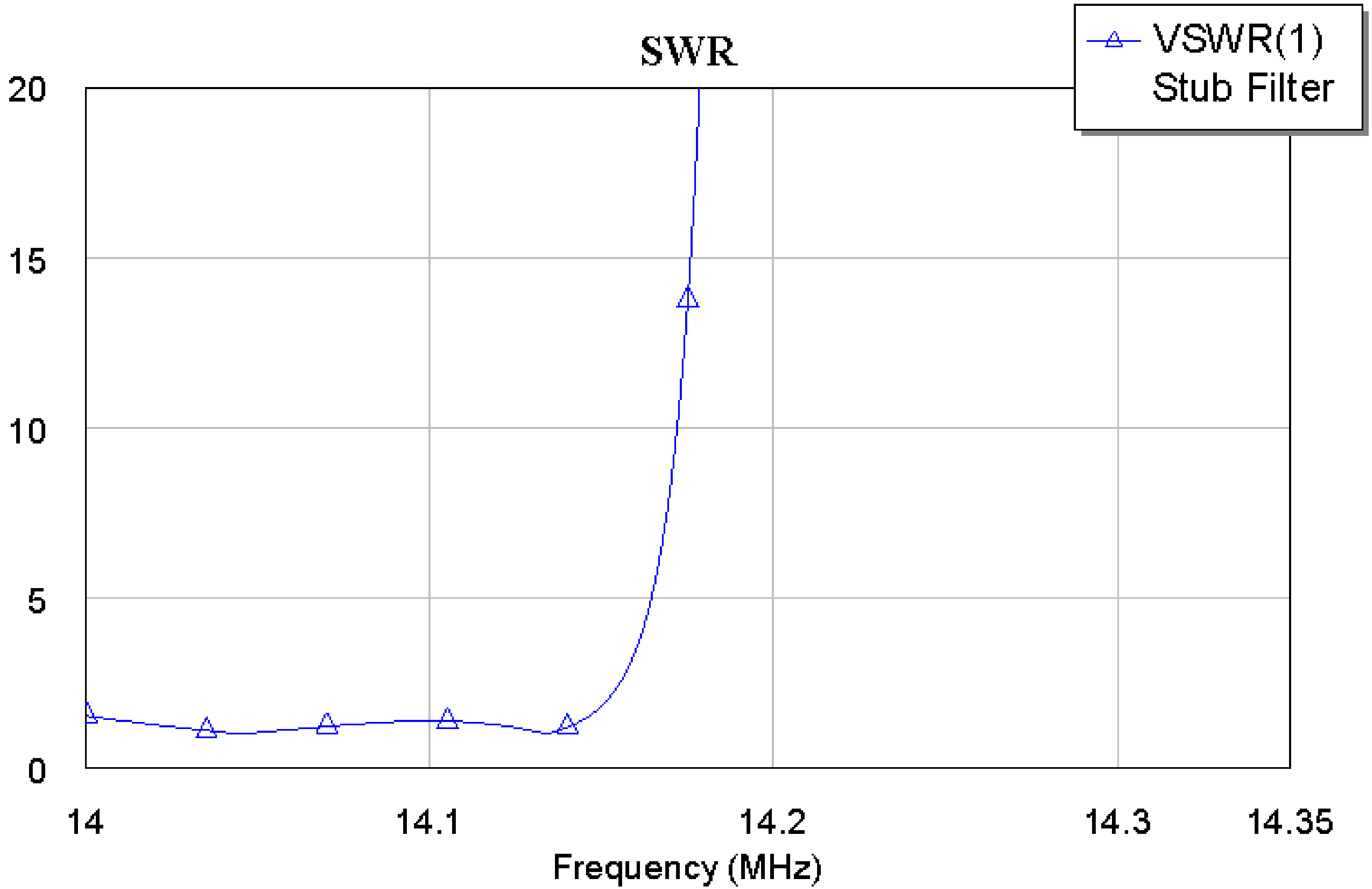
F3 = 15.24 MHz
Z3 = 79.21 Ω

L1 = 7.895 nH
L3 = 1130.3 nH
L5 = 126.9 nH
L7 = 163.0 nH

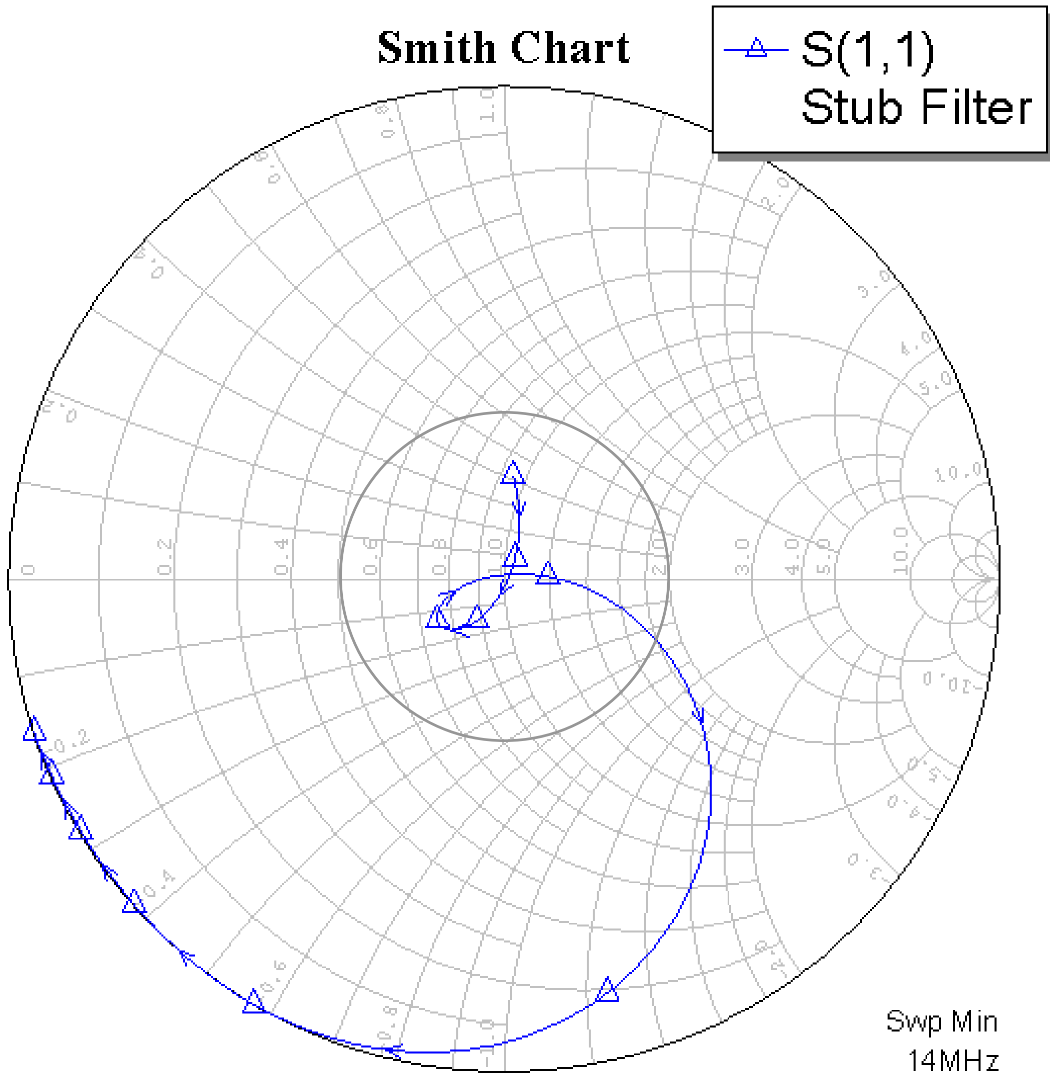
20-Meter CW Pass, Phone Reject Performance



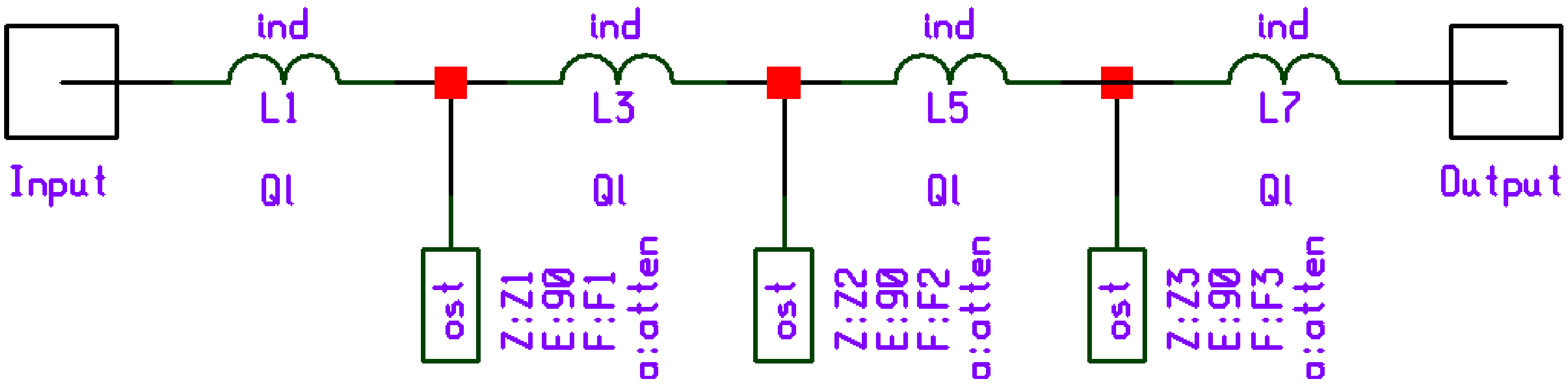
Input SWR


SWR
VSWR(1)
Stub Filter
20
15
10
5
0
14
14.1
14.2
14.3
14.35
Frequency (MHz)

Input Impedance on Smith Chart



Example 3: 3-Stub Filter w/ Losses, Optimized by ARD



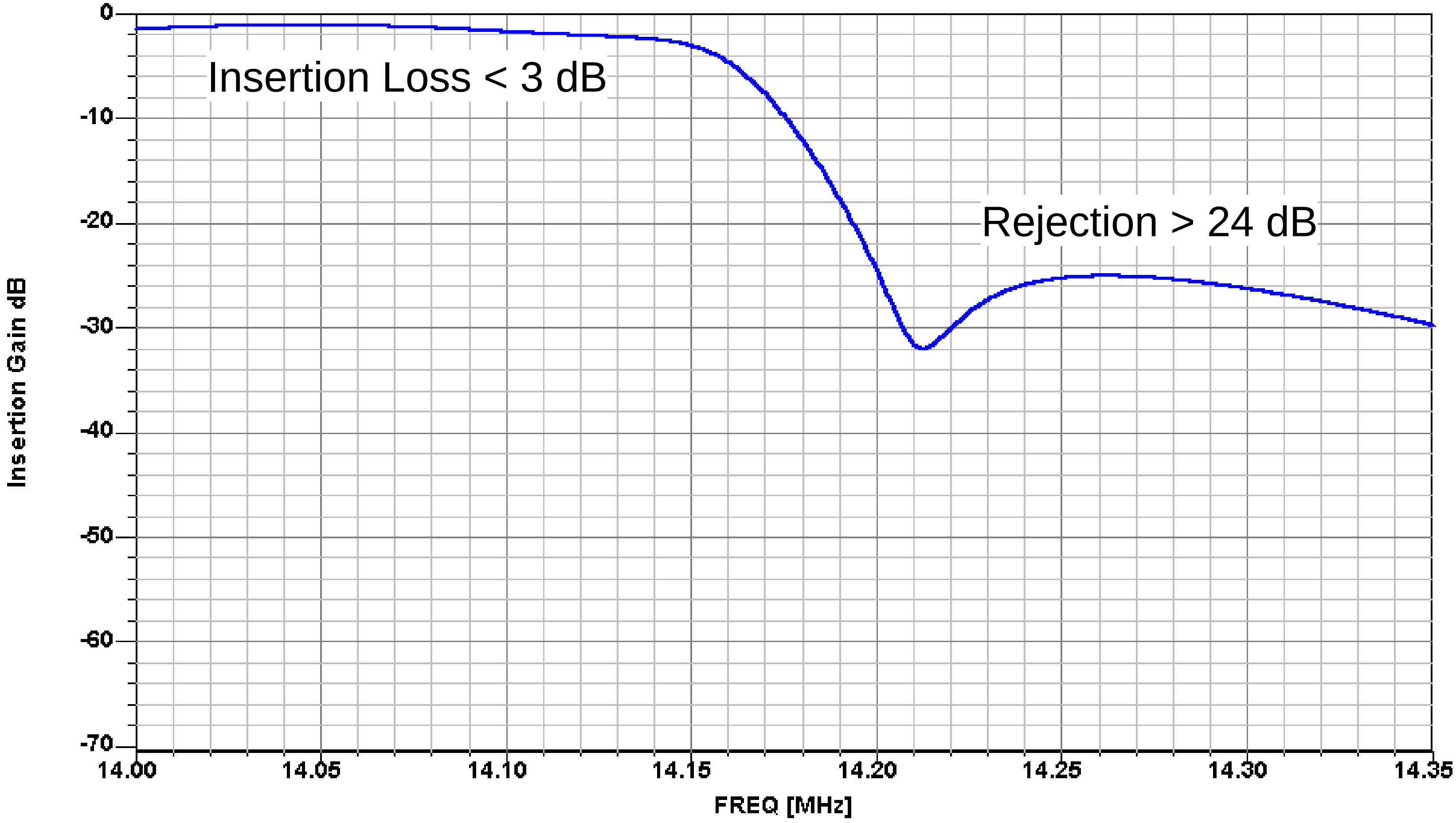
F1 = 14.537 MHz
Z1 = 200 Ω
atten = 0.03 dB/ λ

F2 = 14.211 MHz
Z2 = 200 Ω
atten = 0.03 dB/ λ

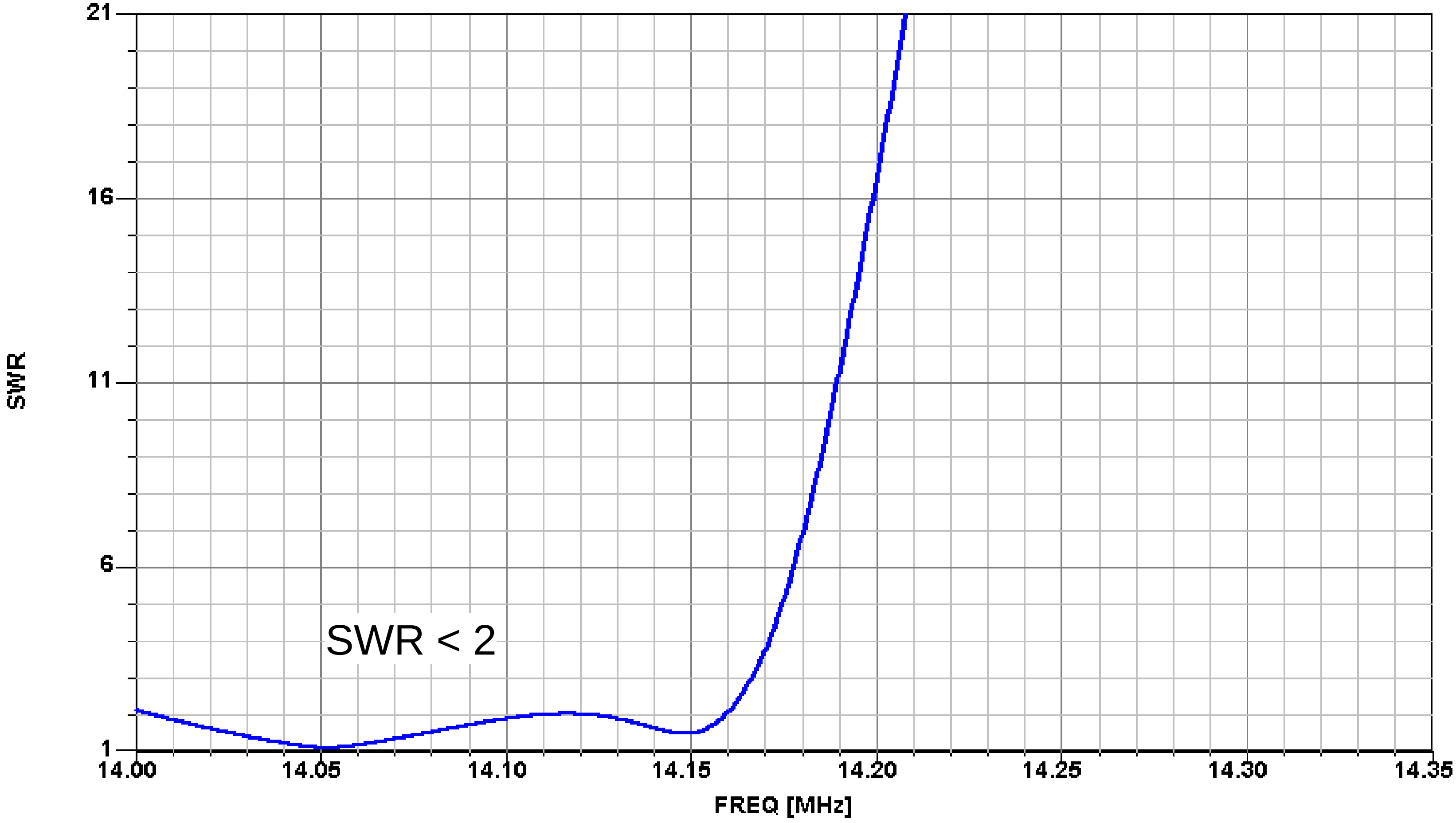
F3 = 14.686 MHz
Z3 = 122 Ω
atten = 0.03 dB/ λ

L1 = 5.354 nH
L3 = 116.3 nH
L5 = 99.21 nH
L7 = 4.897 nH
Q_L = 200

20-Meter CW Pass, Phone Reject Performance

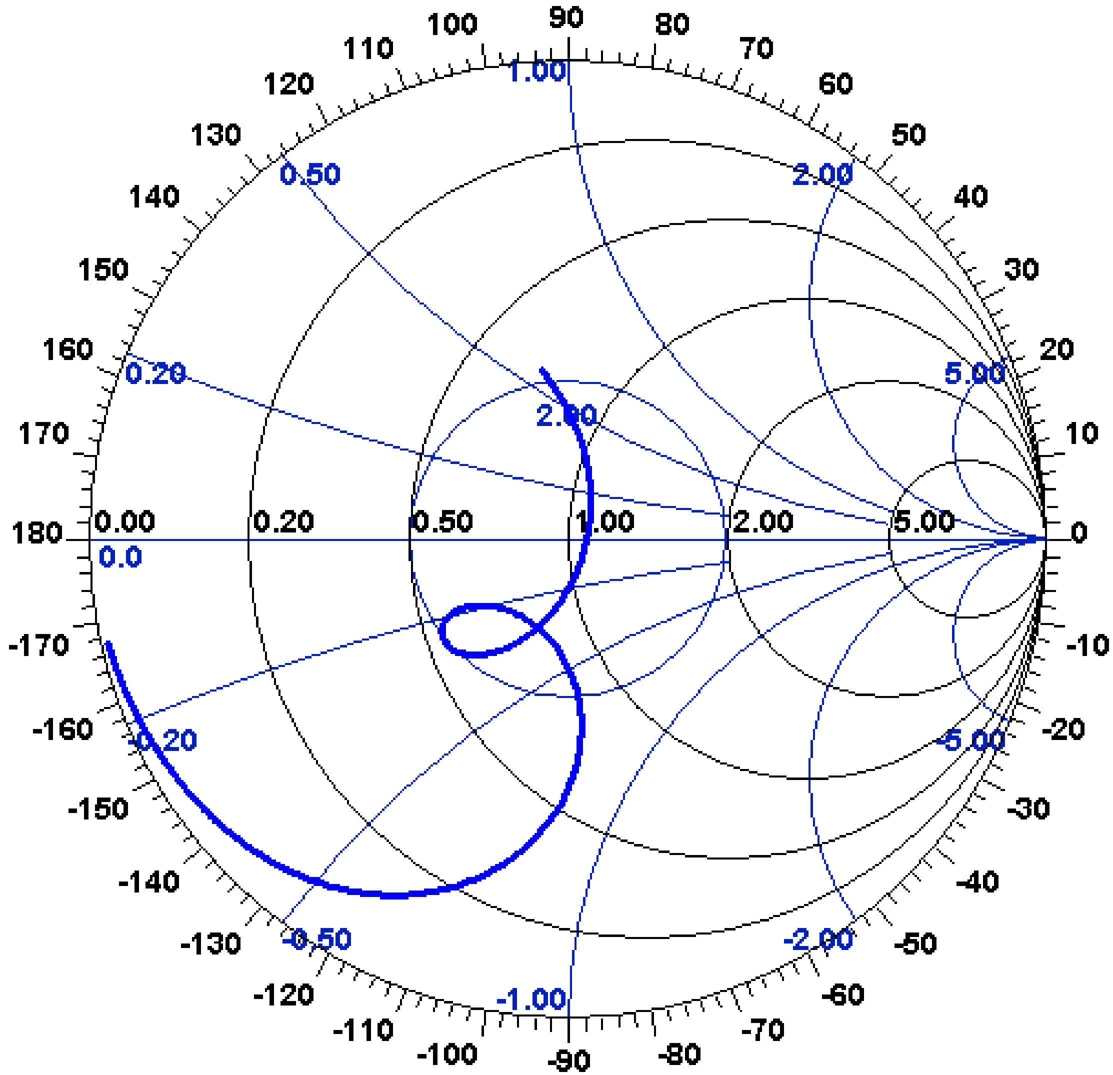


Input SWR



21
16
11
6
1
SWR
14.00
14.05
14.10
14.15
14.20
14.25
14.30
14.35
FREQ [MHz]
SWR < 2

Input Impedance on Smith Chart



Summary

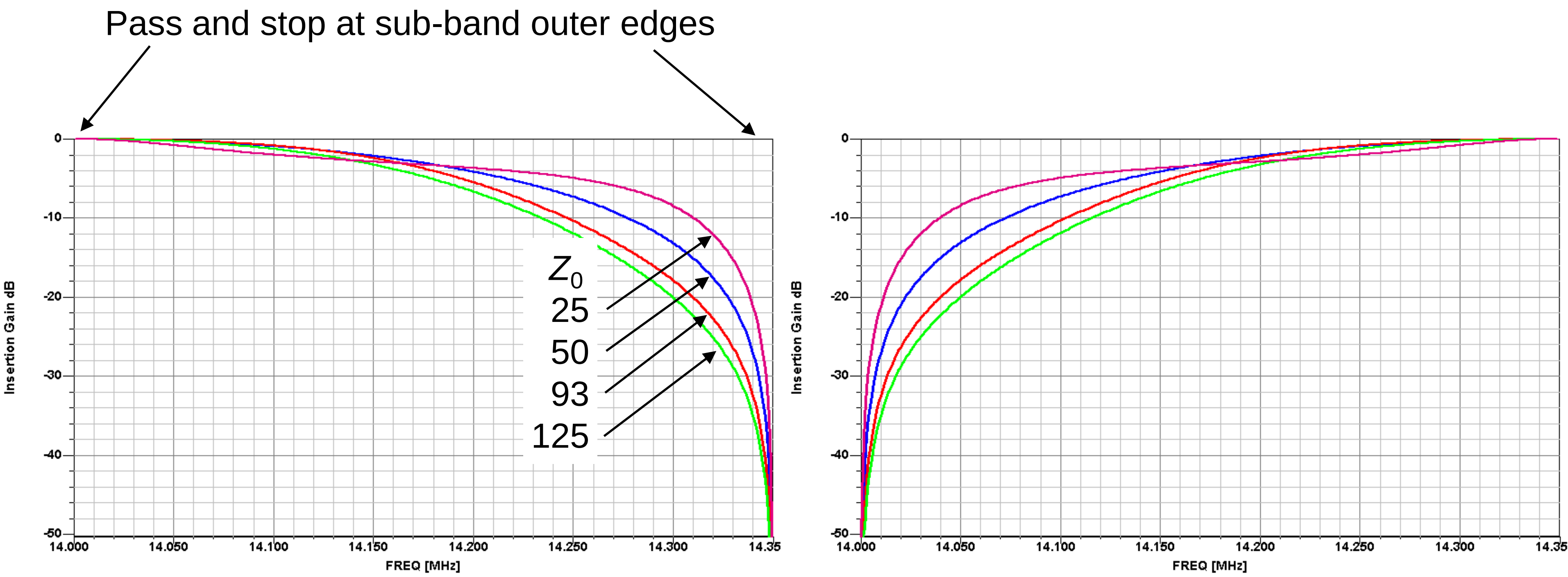
- **Field Day 20-meter sub-band filters were studied**
- **Neither 1-stub nor 2-stub filters were found that met the performance objectives**
- **Determined that 3rd order elliptic lumped element filter would work**
- **A similar 3-stub filter was found that has acceptable performance**
  - SWR < 2 in the "pass" sub-band
  - Insertion loss < 3 dB in the "pass" sub-band ← Determined by losses
  - Rejection > 24 dB in the "stop" sub-band ← Determined by filter order
- **Stubs require ~ 50.3 × v.f. feet of line in two characteristic impedances**

Sub-Harmonic Stub Filters

Sub-Harmonic Stub Filters

- **Pass and stop frequencies can be placed arbitrarily close together by using electrically-long stubs**
- **Set the stub's fundamental frequency low enough such that the pass and stop frequencies are even-odd or odd-even harmonics of the fundamental**
- **The method can be extended to three frequencies, where each is a pass or stop, provided the frequencies are rationally related and relatively prime**
- **This technique requires long line lengths and so is best suited to UHF frequencies**
- **The following example shows a sub-harmonic stub for the 20-meter sub-band filter problem**
- **Long stub length makes the solution impractical for HF, but method is educational**

Example 4: Sub-Band Filters via a Sub-Harmonic Stub

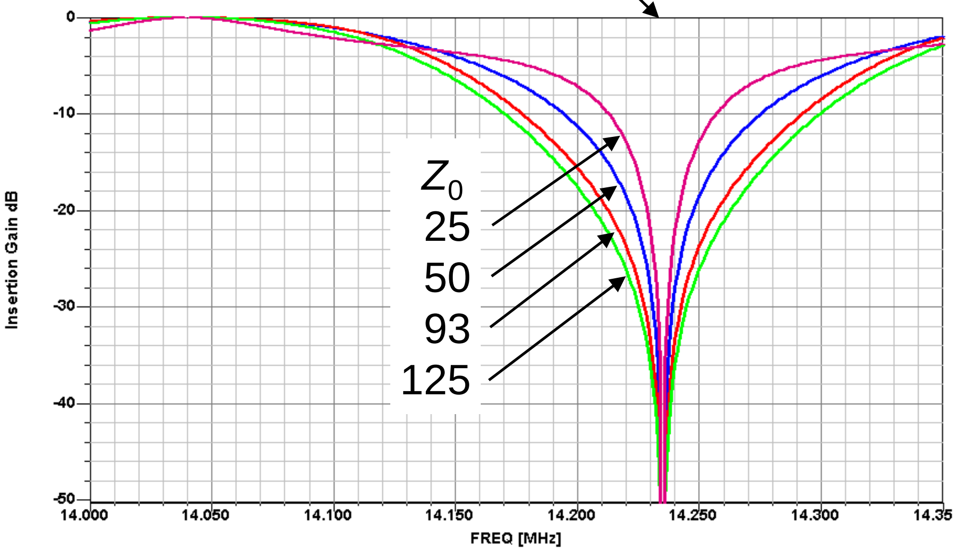


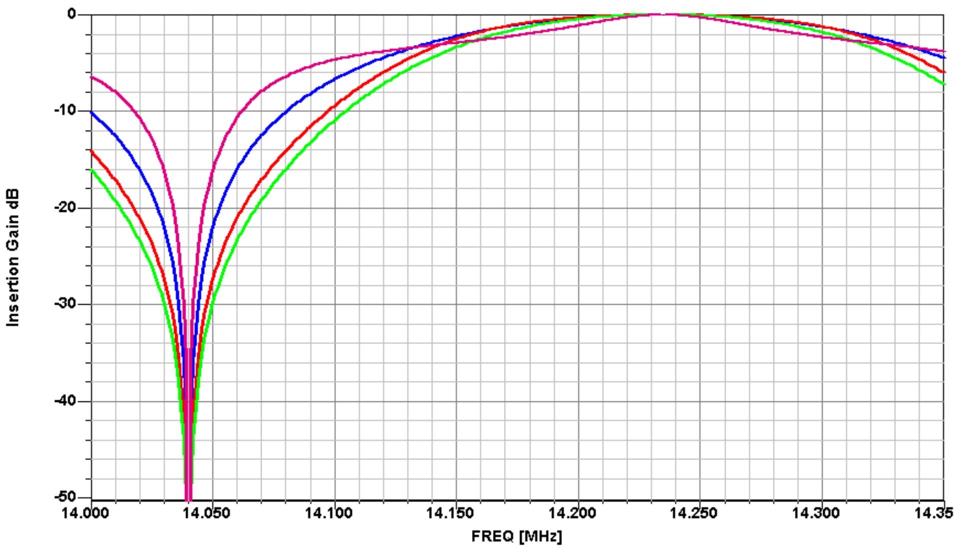
<u>Open-circuit stubs pass even harmonics</u>
Fundamental frequency 350 kHz
$l = \lambda / 4 = 703$ ft. × v.f.
Pass CW sub-band (harmonic 40)
Stop phone sub-band (harmonic 41)

<u>Short-circuit stubs pass odd harmonics</u>
Fundamental frequency 350 kHz
$l = \lambda / 4 = 703$ ft. × v.f.
Pass phone sub-band (harmonic 40)
Stop CW sub-band (harmonic 41)

Example 5: Decreasing Pass-to-Stop by a Longer Stub

Pass and stop at sub-band centers





<u>Open-circuit stubs pass even harmonics</u>
Fundamental frequency 195 kHz
$l = \lambda / 4 = 1{,}262$ ft. $\times$ v.f.
Pass CW sub-band (harmonic 72)
Stop phone sub-band (harmonic 73)

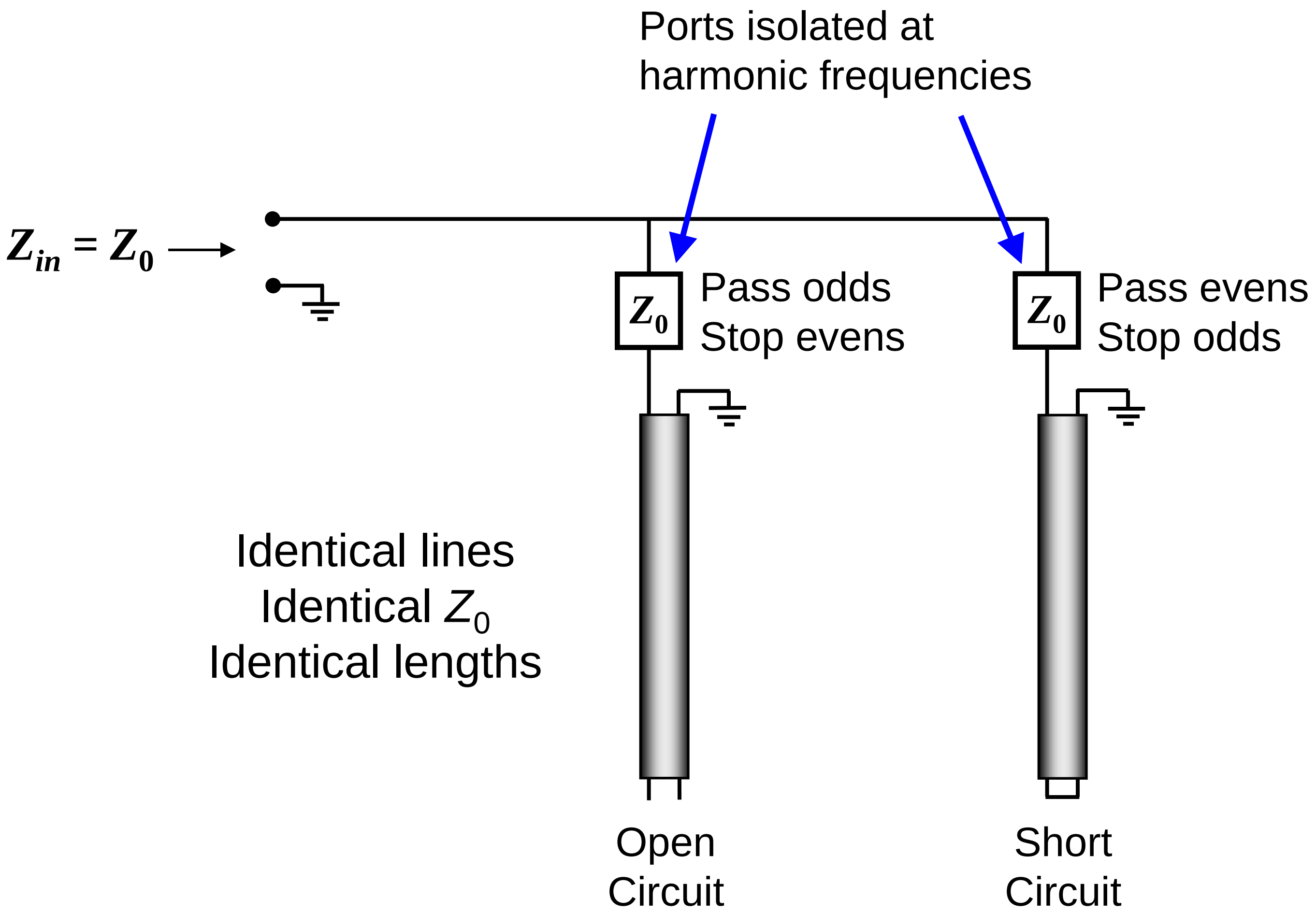
<u>Short-circuit stubs pass odd harmonics</u>
Fundamental frequency 195 kHz
$l = \lambda / 4 = 1{,}262$ ft. $\times$ v.f.
Pass phone sub-band (harmonic 72)
Stop CW sub-band (harmonic 73)

Reflectionless Stub Filters

Reflectionless Filters

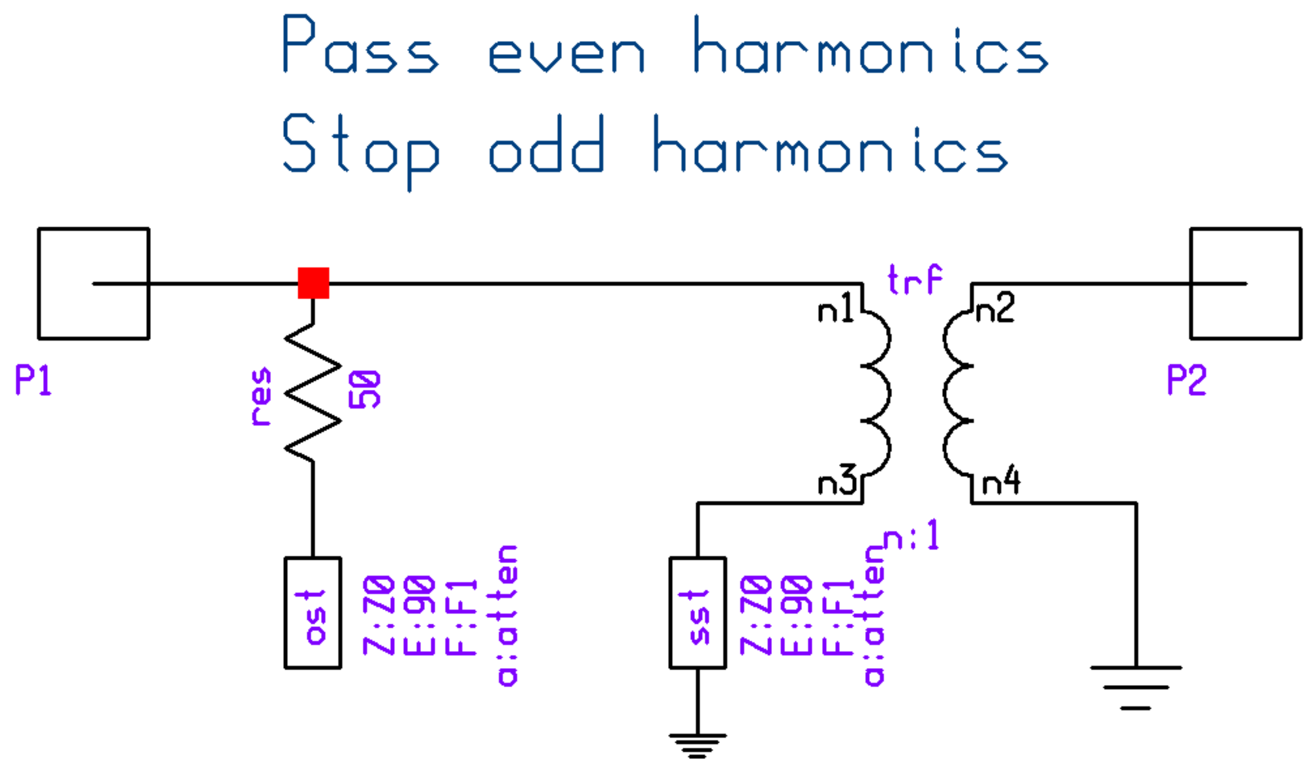
- **Filter by absorption instead of reflection**
- **Can be viewed as a lossless 3-port or lossy 2-port network**
- **2-port implementation requires internal resistor**
- **3-port implementation gives diplexer function**
  - Even harmonic bands couple to one port
  - Odd harmonic bands couple to the other port
  - Ports must be terminated with matched impedances
- **Applications**
  - Connect a multiband transmitter to two antennas on different bands without using an antenna switch
  - Connect two transceivers to a single antenna on different bands

Reflectionless Filter Using Complementary Stubs

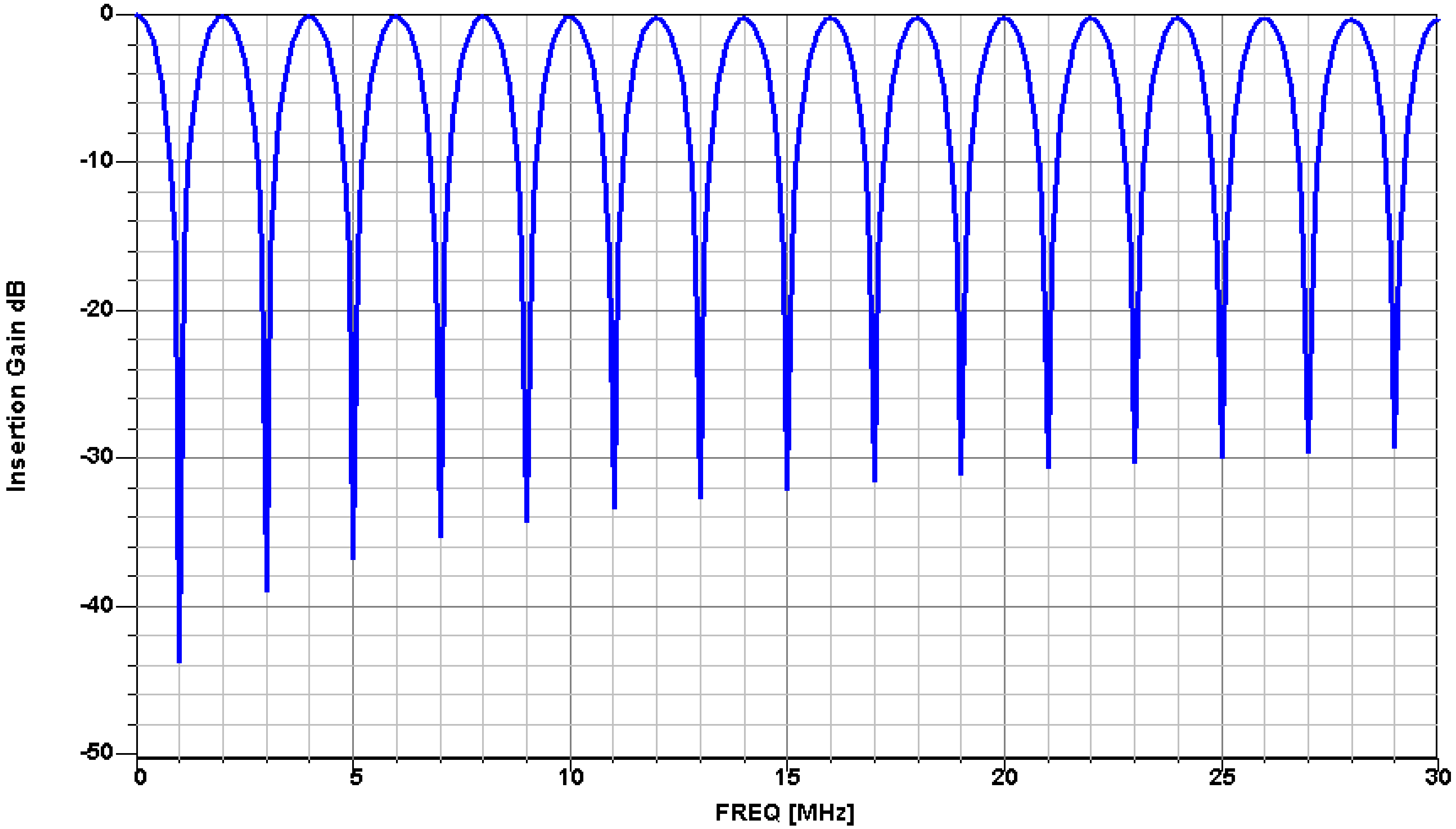


Complementary stubs provide constant input resistance and output port isolation at multiple pass and stop frequencies.

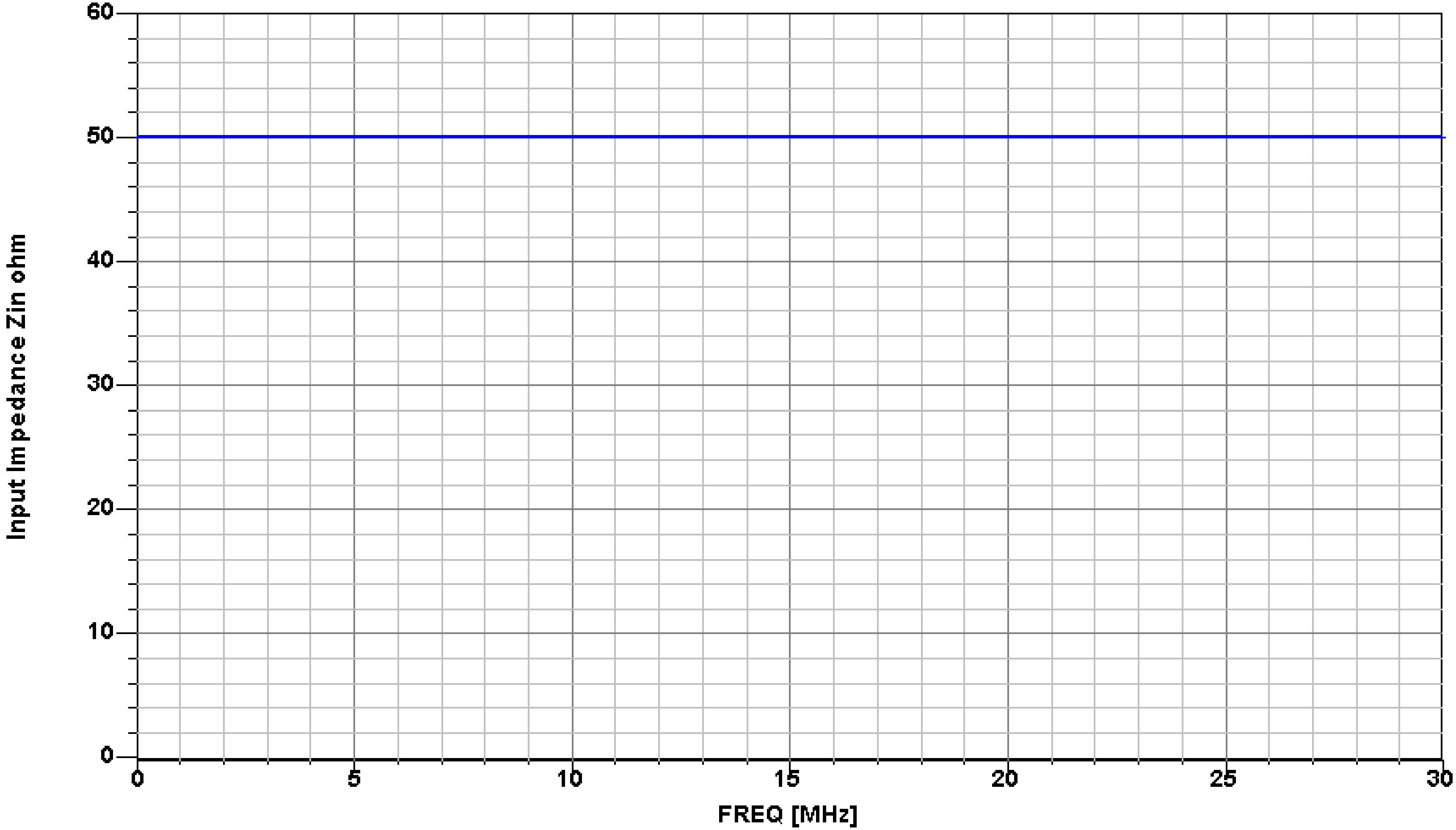
A 50-Ω Reflectionless Stub Filter



Insertion Gain from Input to Output Port



Input Impedance of 50-Ω Terminated Filter



Commensurate Filters

Paul Irving Richards, 1923-1978

Courtesy of Harvard University

Commensurate Filters

- Commensurate filters: all transmission line sections have lengths that are integer multiples of a unit length l
- Commensurate stub filters use transmission line stubs in place of capacitors and inductors
- Starting from a lumped-element prototype, replace all inductors and capacitors with short stubs, setting inductance L and capacitance C by the choice of integer n and Z_0 for each stub
- For inductors, use short-circuited stubs of length nl

$$L = \frac{Z_0\, n\, l}{c} = Z_0\, \tau$$

- For capacitors, use open-circuited stubs of length nl

$$C = \frac{n\, l}{Z_0\, c} = \frac{\tau}{Z_0}$$

Facts about Commensurate Stub-Resistor Networks

- **P.I. Richards's (1948) transformation extended lumped-element network theories of realizability, synthesis, and filtering to a class of transmission line networks**
  - Stub-resistor networks: no capacitors or inductors
  - Synthesis: Brune, Bott-Duffin, Darlington, etc.
  - Filters: Butterworth, Chebyschev, Elliptic, etc.
- **Commensurate filters act like lumped-element filters from *d-c* up to a given frequency, above which the frequency response repeats periodically**

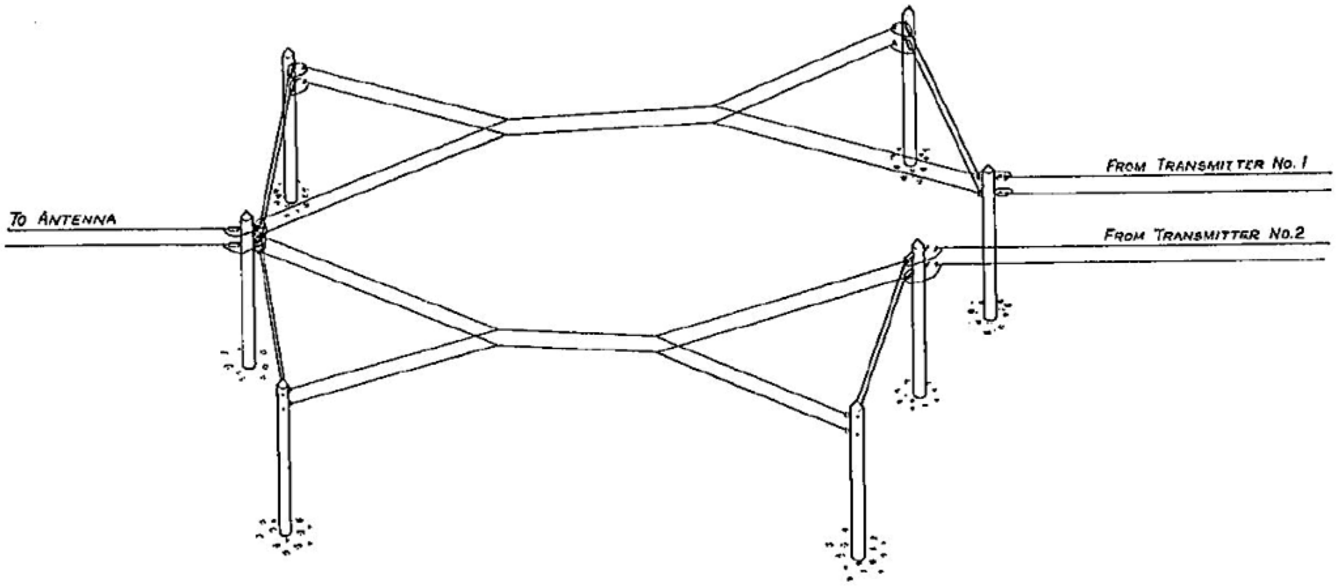
Re-Entrant Transmission Line Filters

Andrew Alford, 1904-1992

Courtesy of IEEE

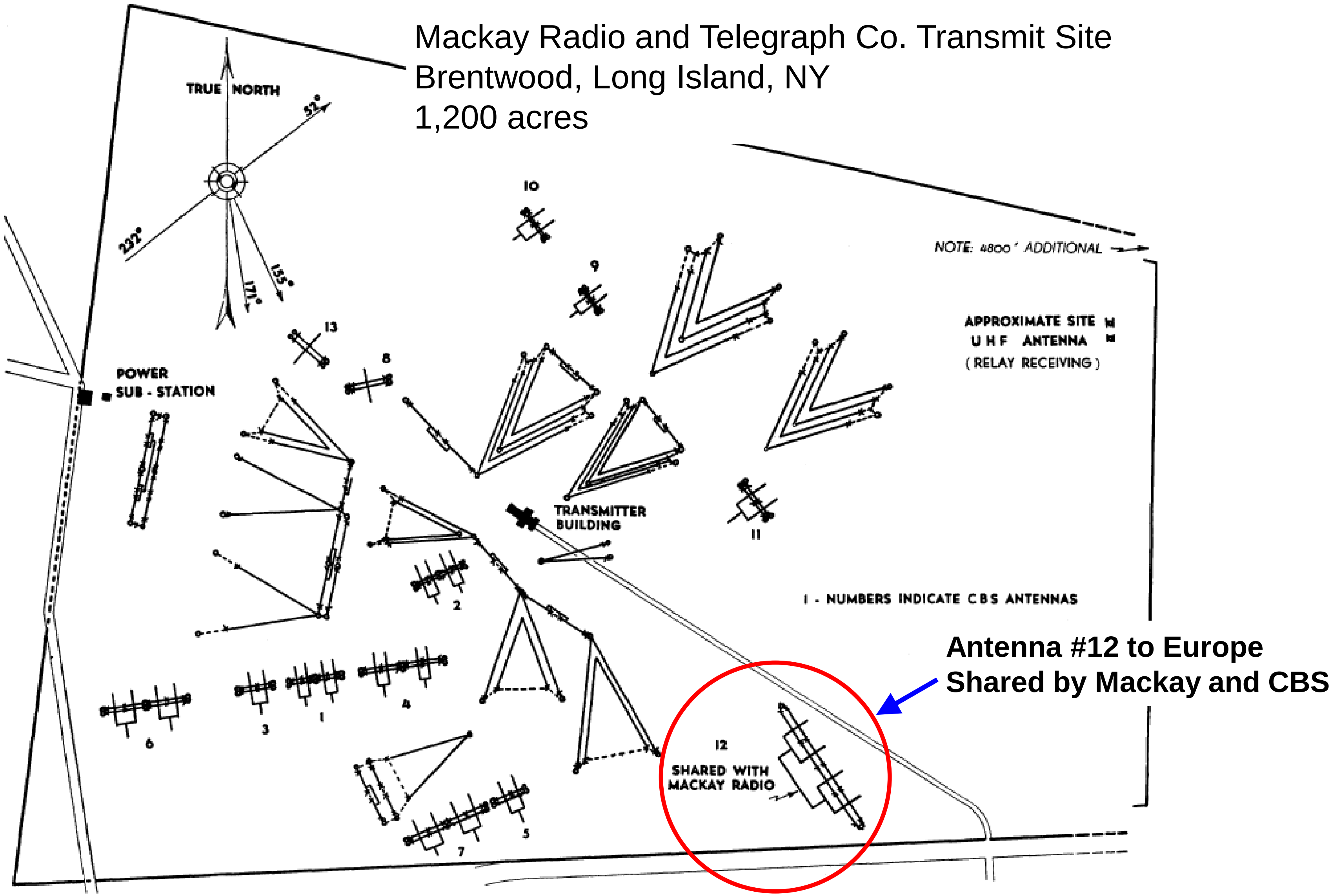
Re-Entrant Filter – Type 1

- **Introduced by A. Alford in 1939**
- **Transmission lines function as 2-port devices with both ends of the line connected into the network**

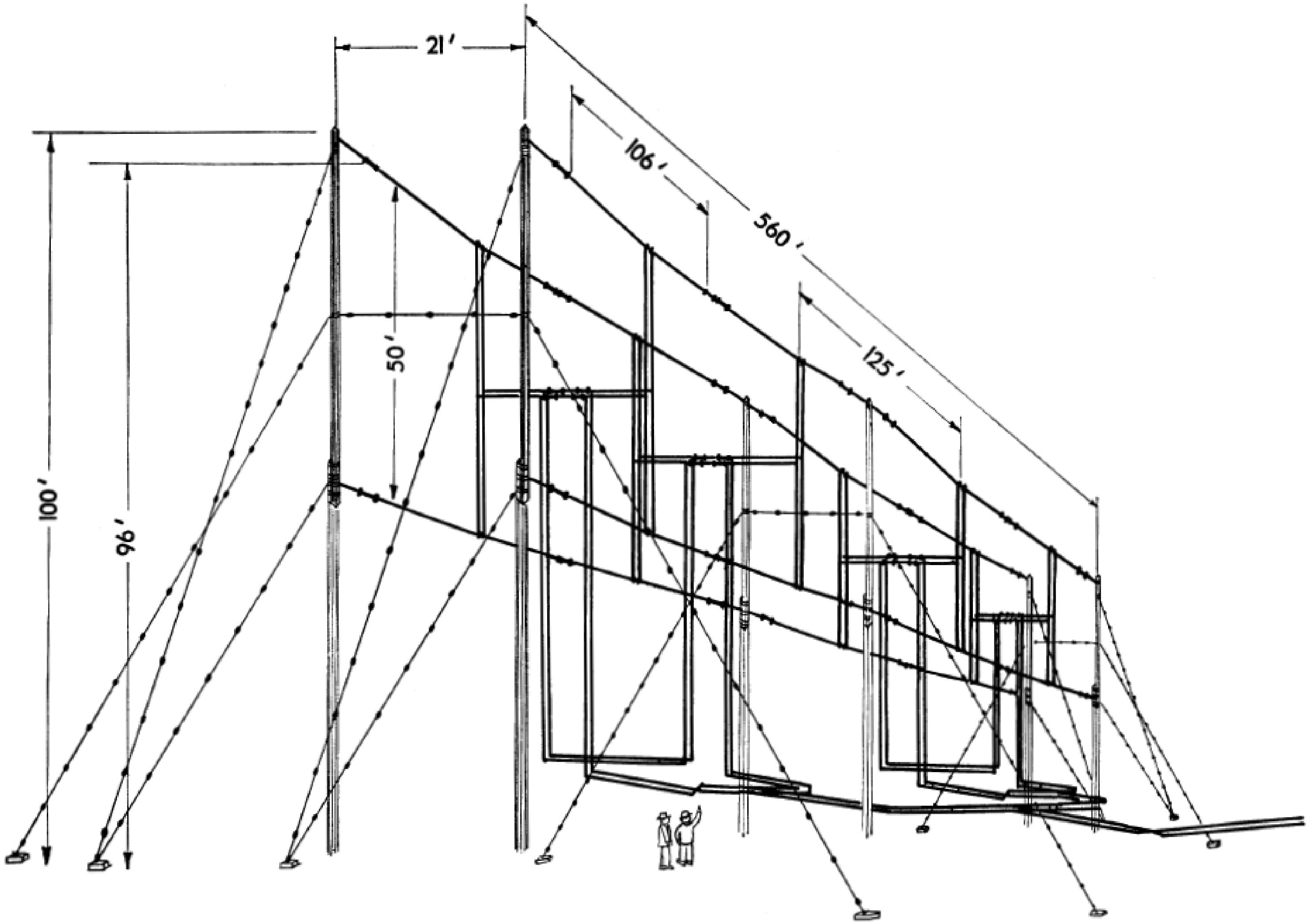


Re-entrant diplexer, Mackay Radio and Telegraph Co., circa 1939

CBS WCBX & WCRC Antennas, Brentwood, Long Island



Antenna No. 7 – Antenna No. 12's Little Brother



A.B. Chamberlain, "CBS International Broadcast Facilities," *Proc. IRE*, March 1942

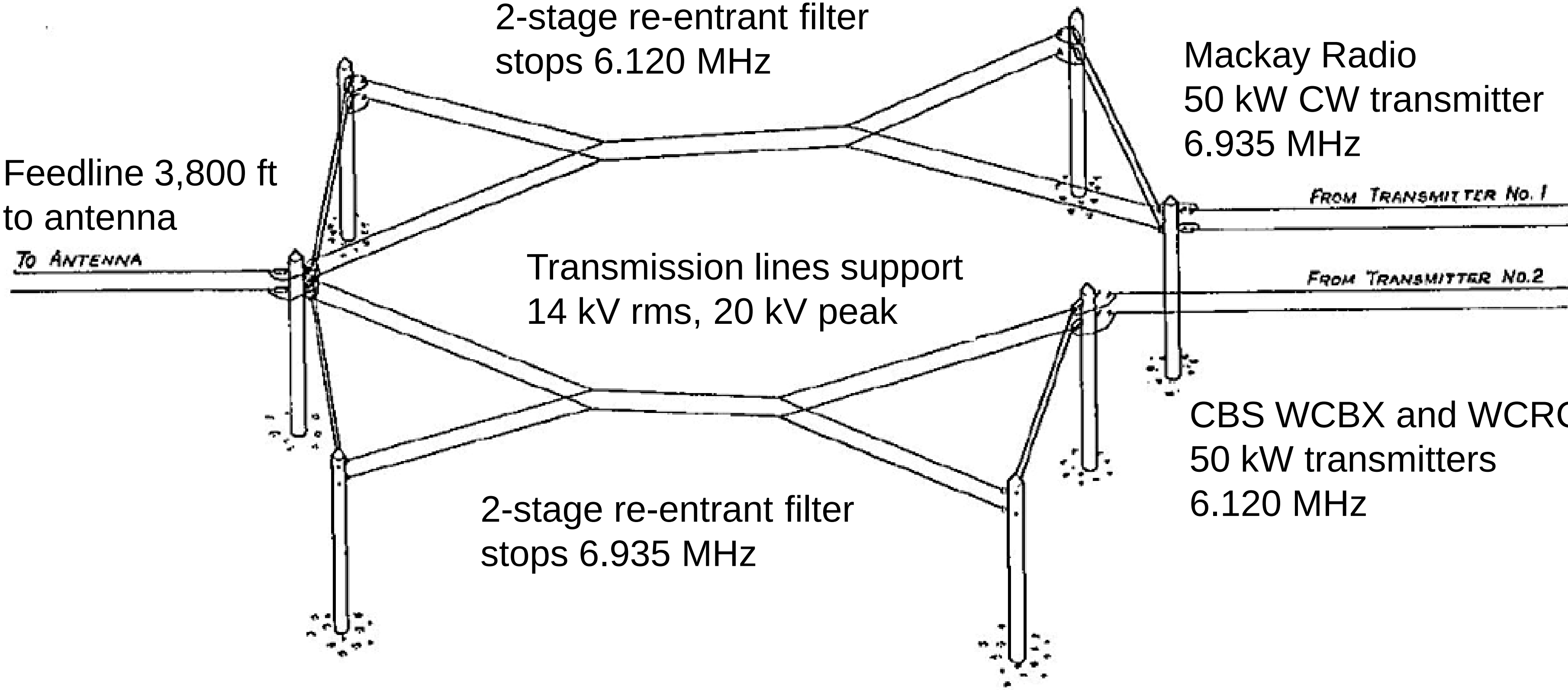
Technical Specifications of Mackay/CBS Diplexer

2-stage re-entrant filter
stops 6.120 MHz

Mackay Radio
50 kW CW transmitter
6.935 MHz

Feedline 3,800 ft
to antenna

Transmission lines support
14 kV rms, 20 kV peak

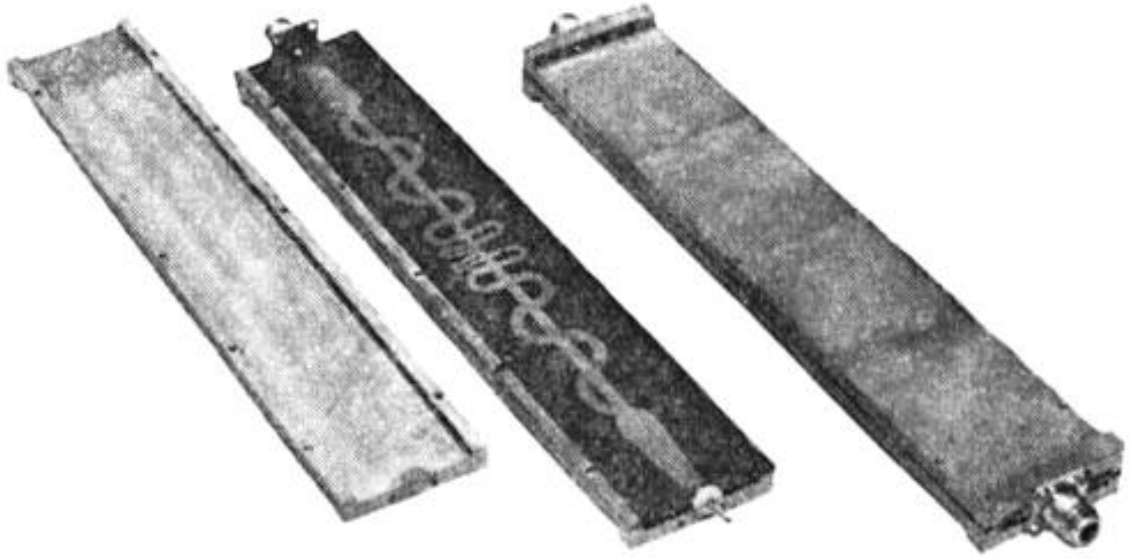


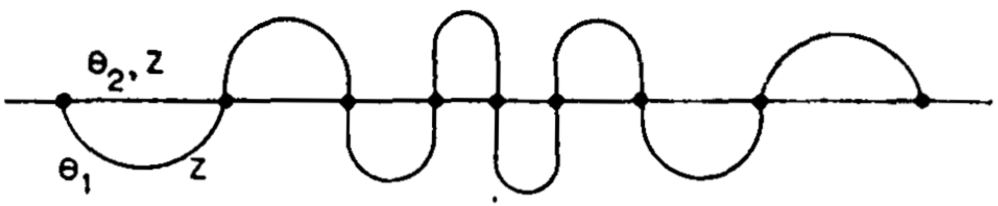
CBS WCBX and WCRC
50 kW transmitters
6.120 MHz

2-stage re-entrant filter
stops 6.935 MHz

Line $Z_0 \approx 550$ ohms
Stopband attenuation > 40-50 dB
Passband attenuation < 0.2-0.3 dB

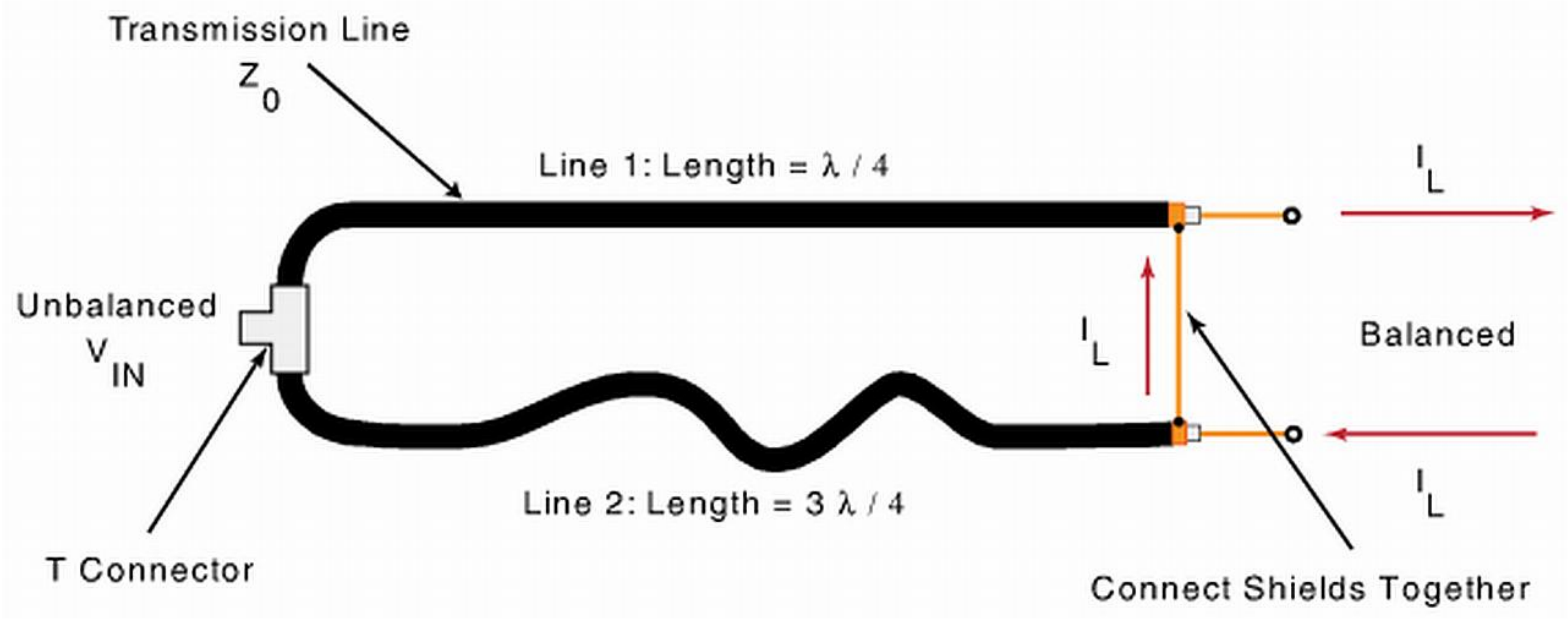
Example 2: 6-Section Tapered Re-Entrant LPF





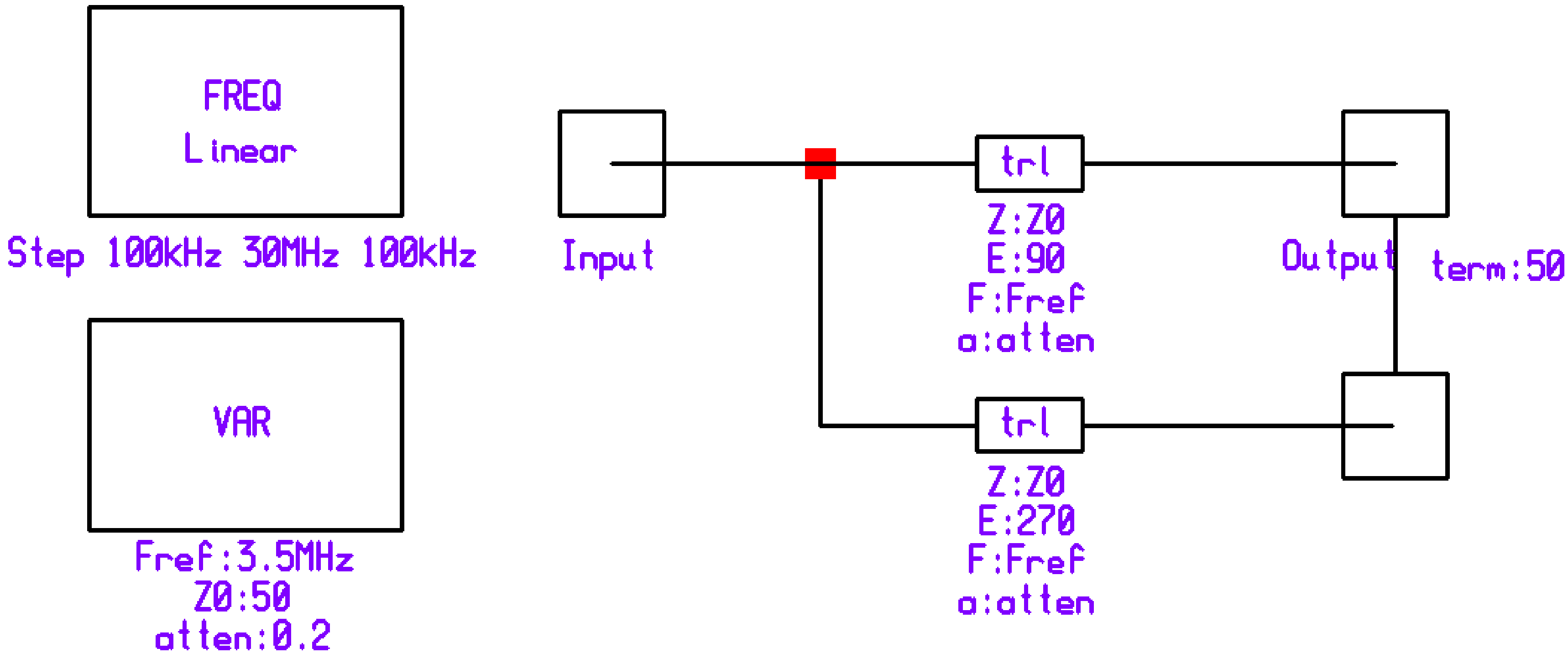
J.M.C. Dukes, "Re-entrant Transmission Line Filter Using Printed Conductors," *Proc. IEE*, Nov. 1957

Example 3: The Q3Q-PS Balun

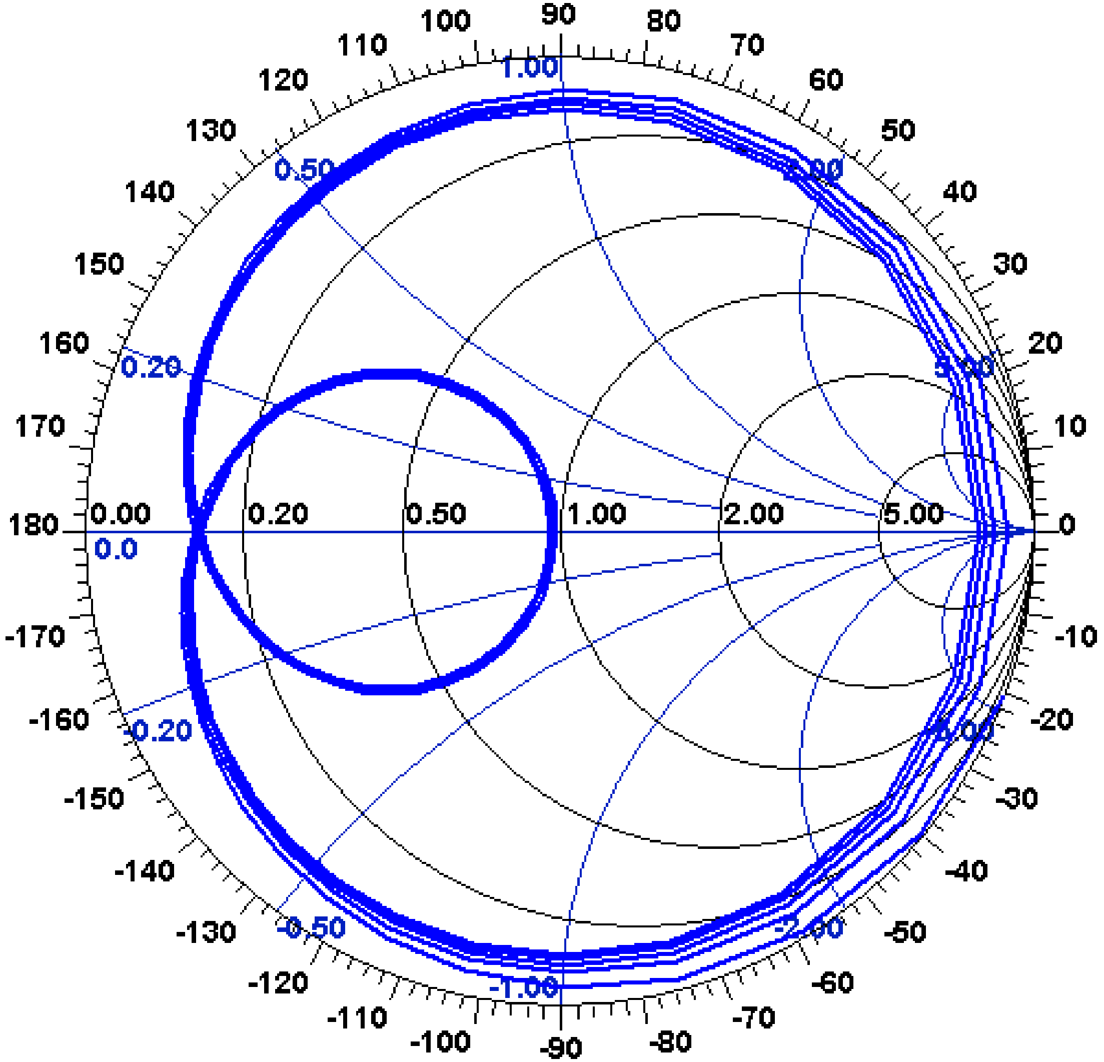


H.W. Silver, N0AX, “Experiment 116: The Quarter-Three-Quarter Wave Balun,” *QST*, Sept. 2012

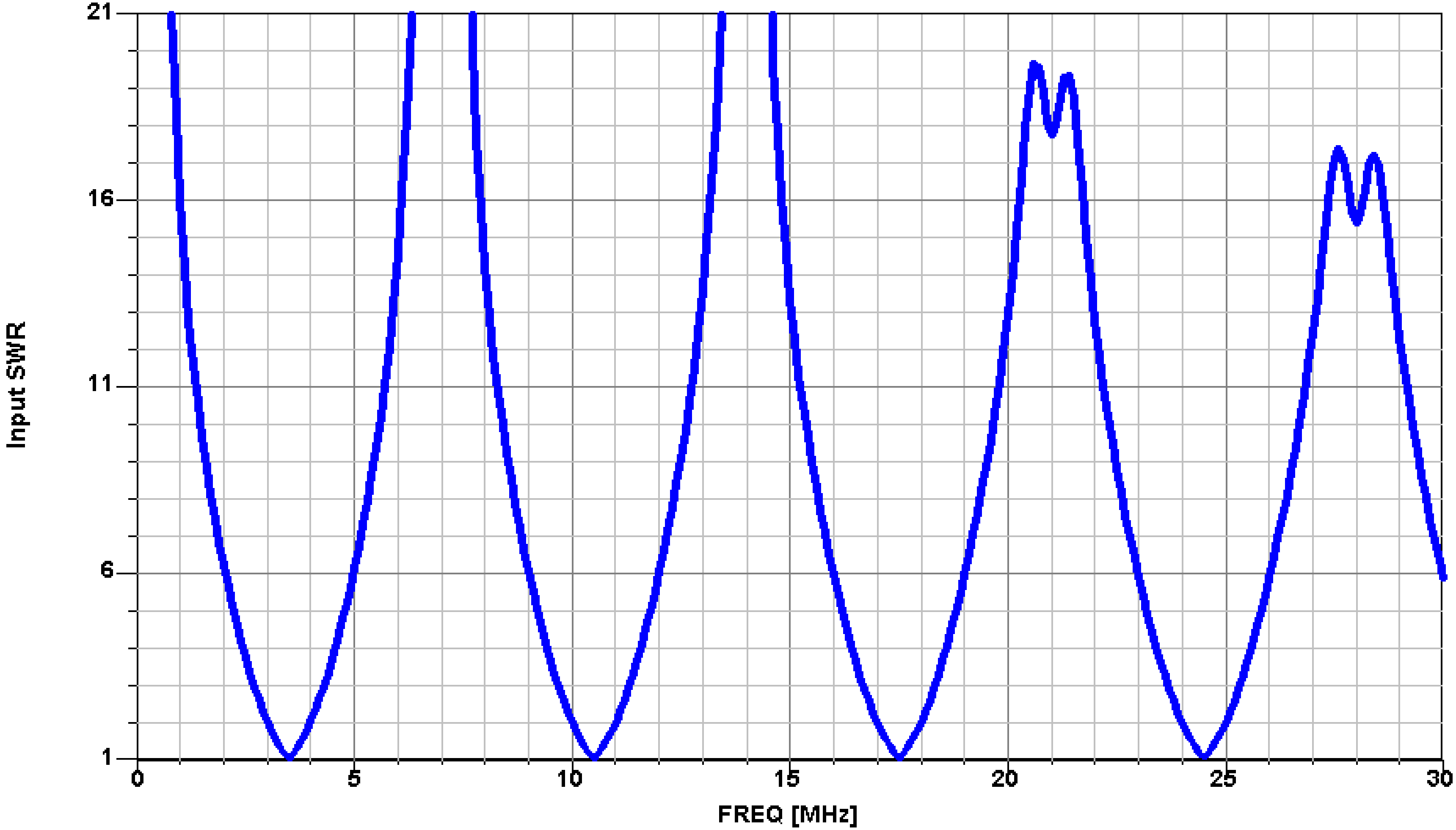
The Q3Q-PS Balun Schematic in Serenade



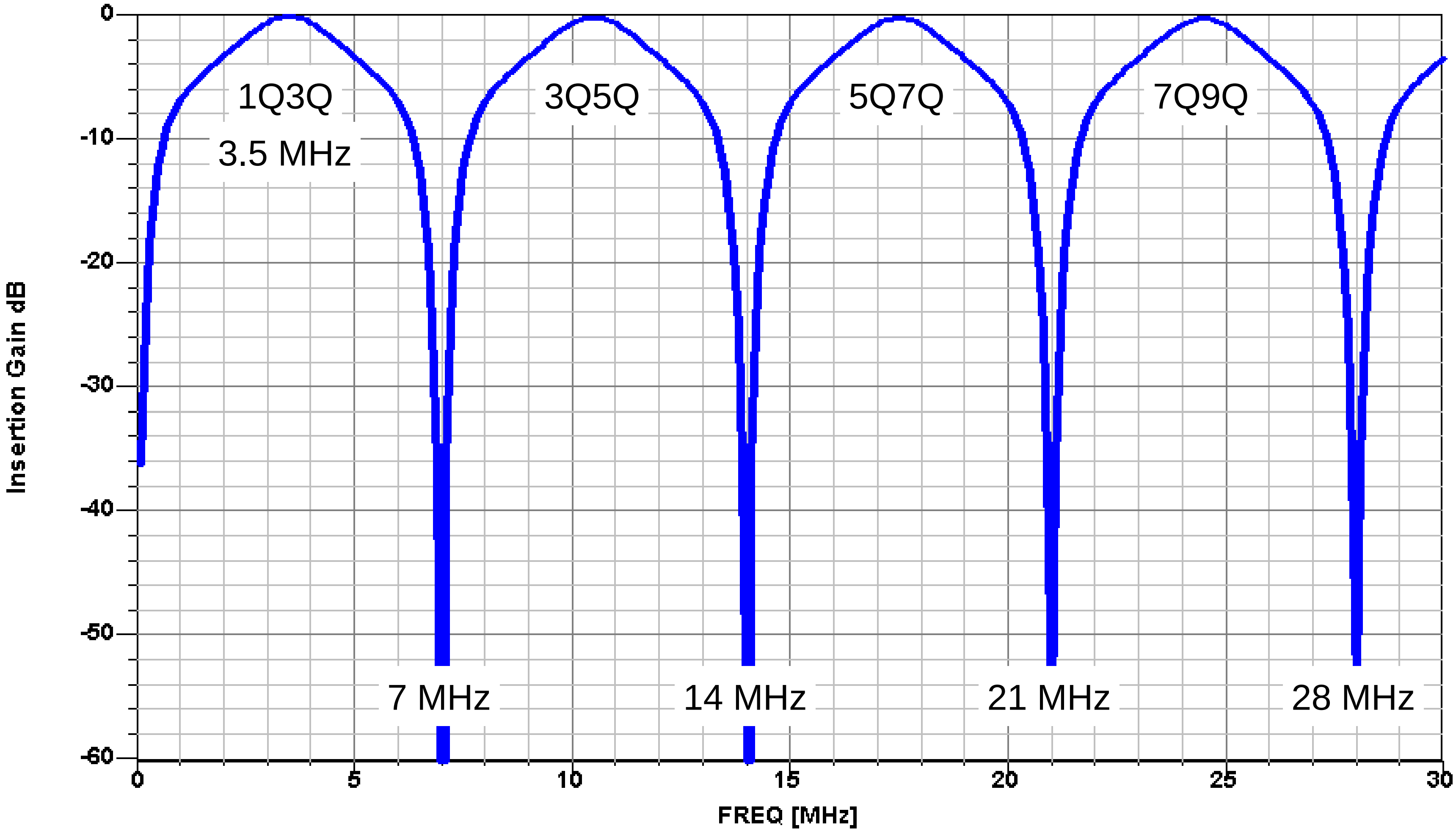
Q3Q-PS Balun Input Impedance on Smith Chart



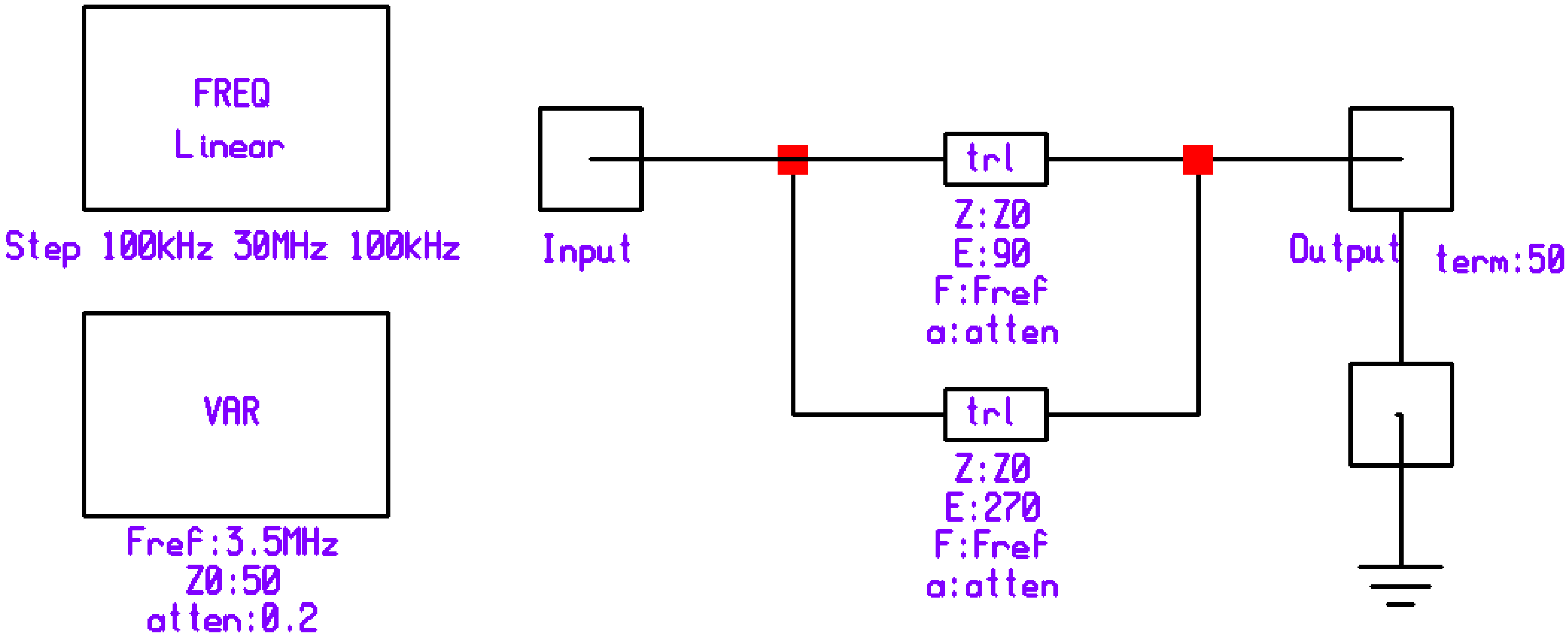
Q3Q-PS Balun Input SWR vs Frequency



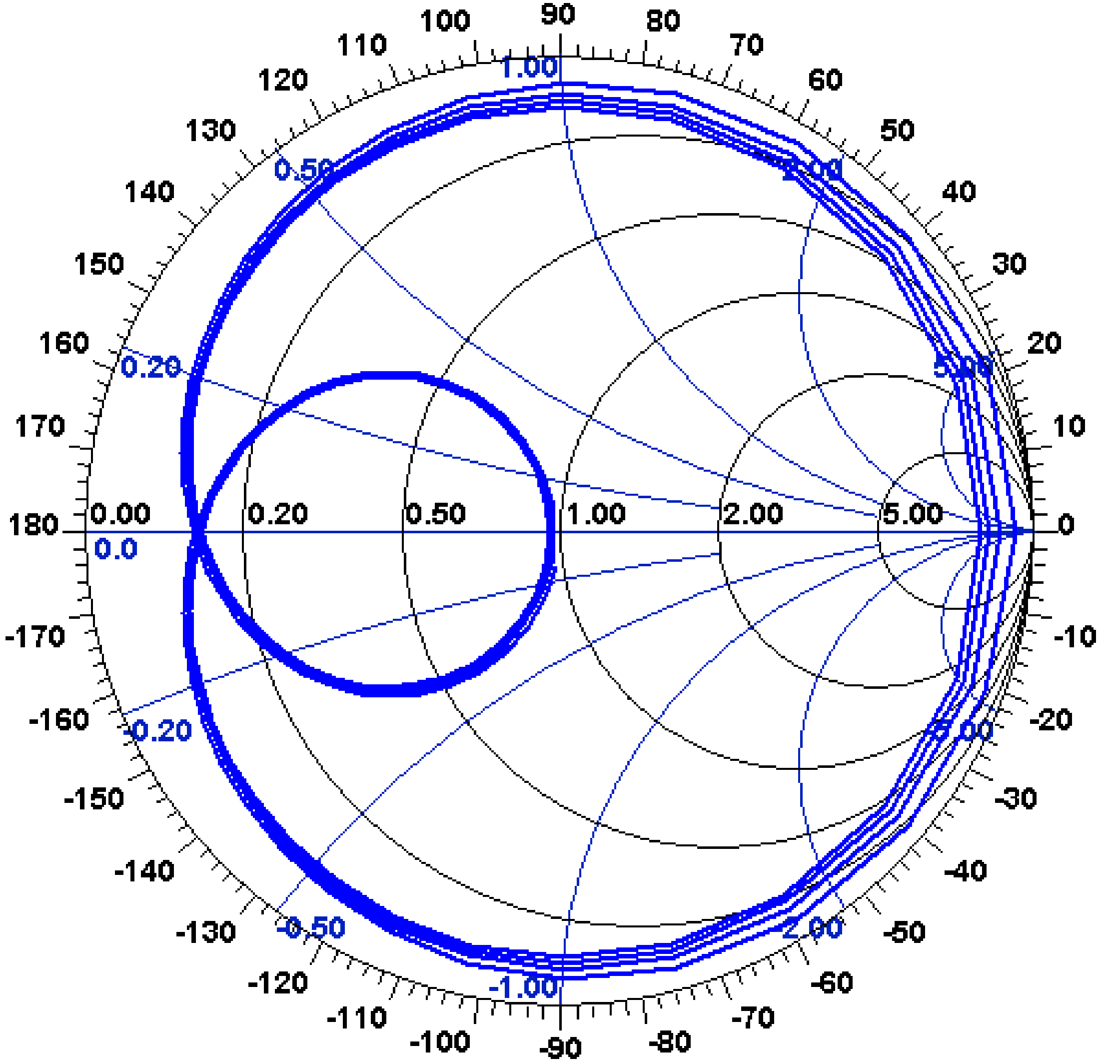
Q3Q Balun Insertion Gain vs Frequency



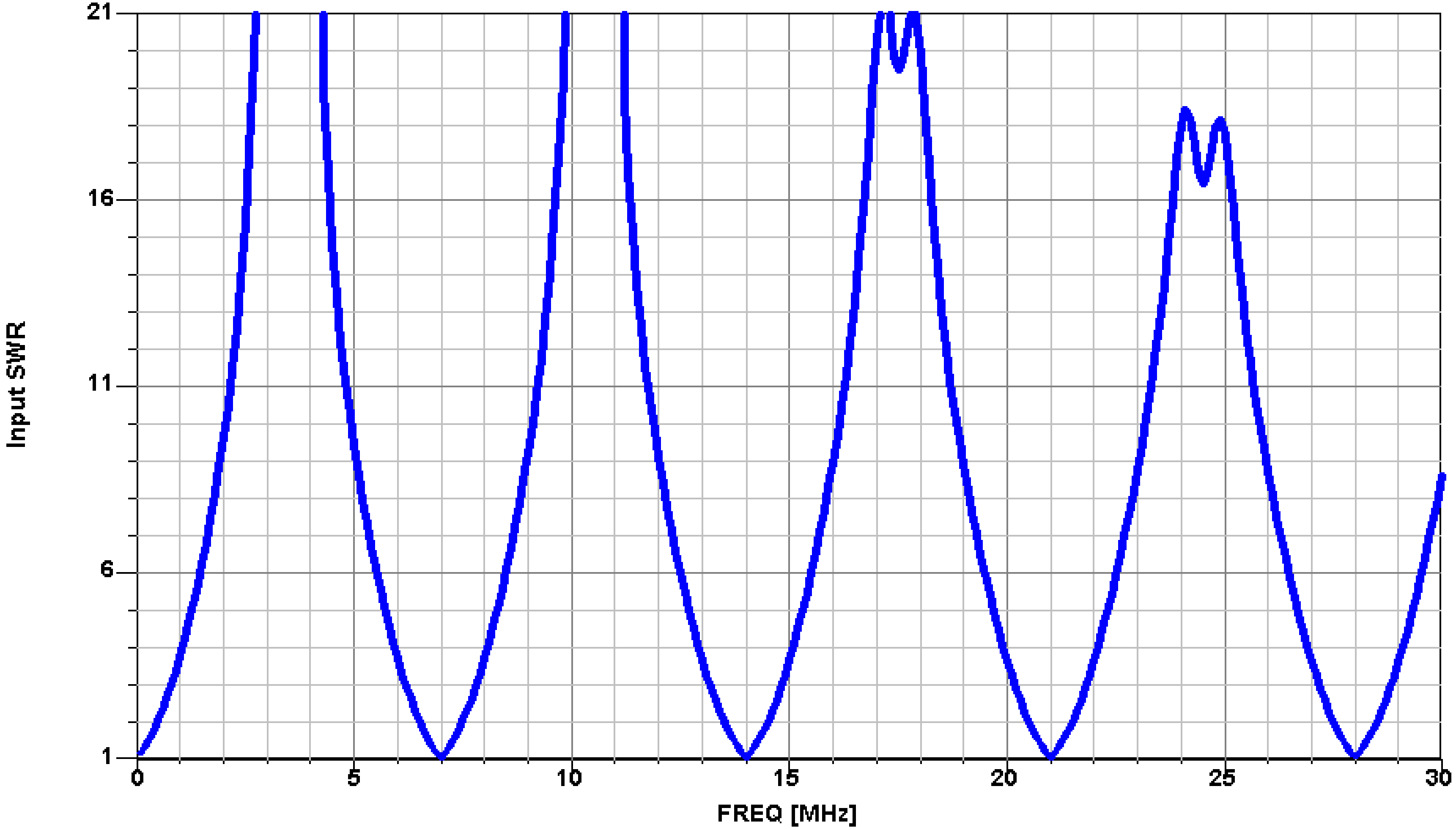
Example 4: Q3Q-PP, Lines Paralleled at Output



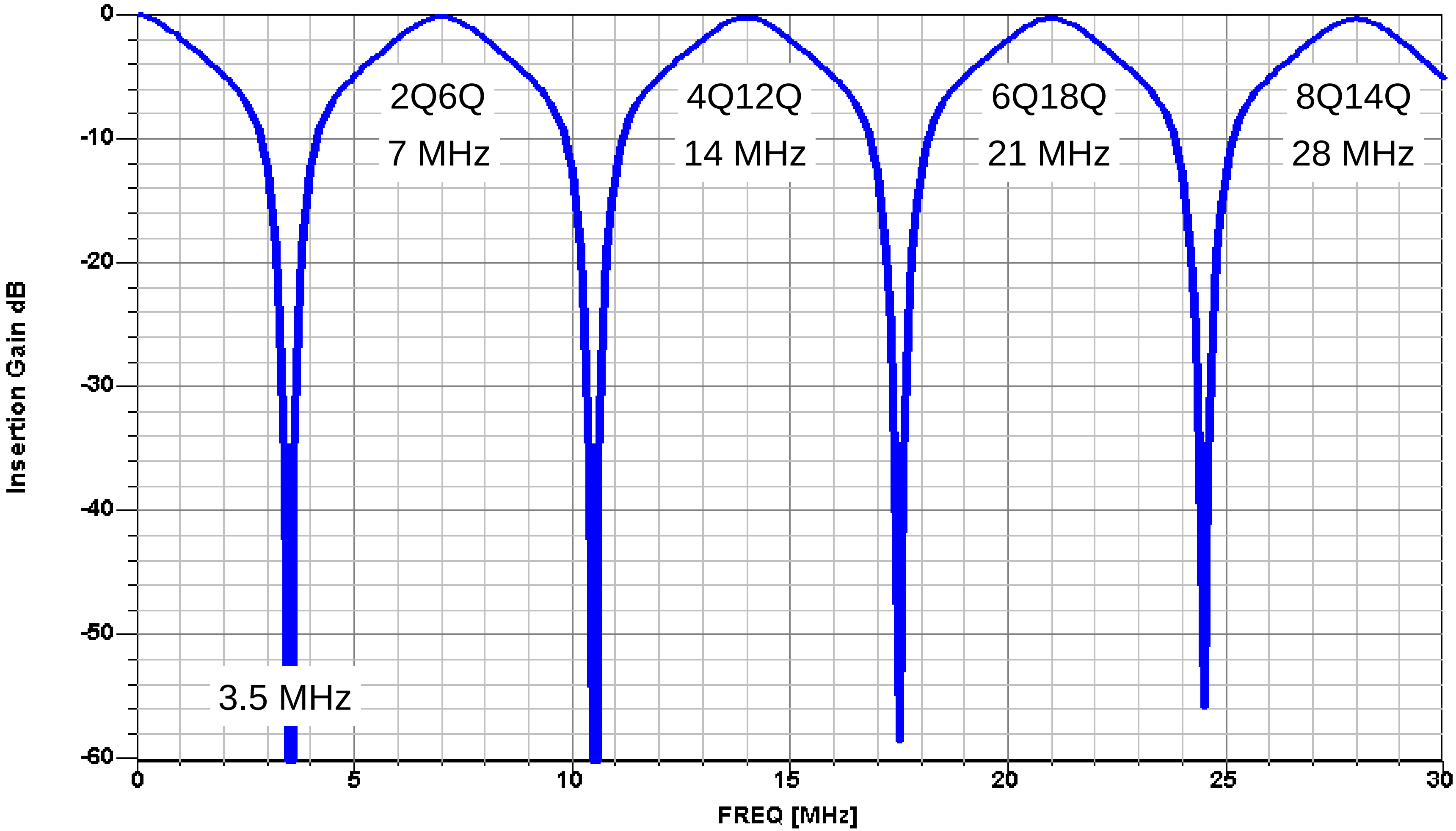
Q3Q-PP Filter Input Impedance on Smith Chart



Q3Q-PP Filter Input SWR vs Frequency

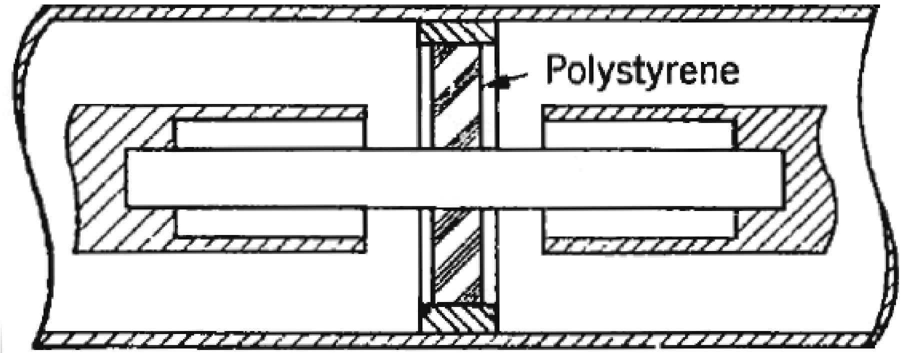


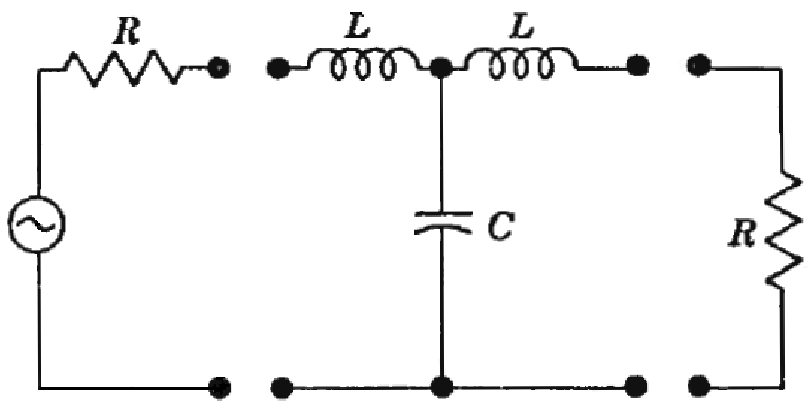
Q3Q-PP Filter Insertion Gain vs Frequency



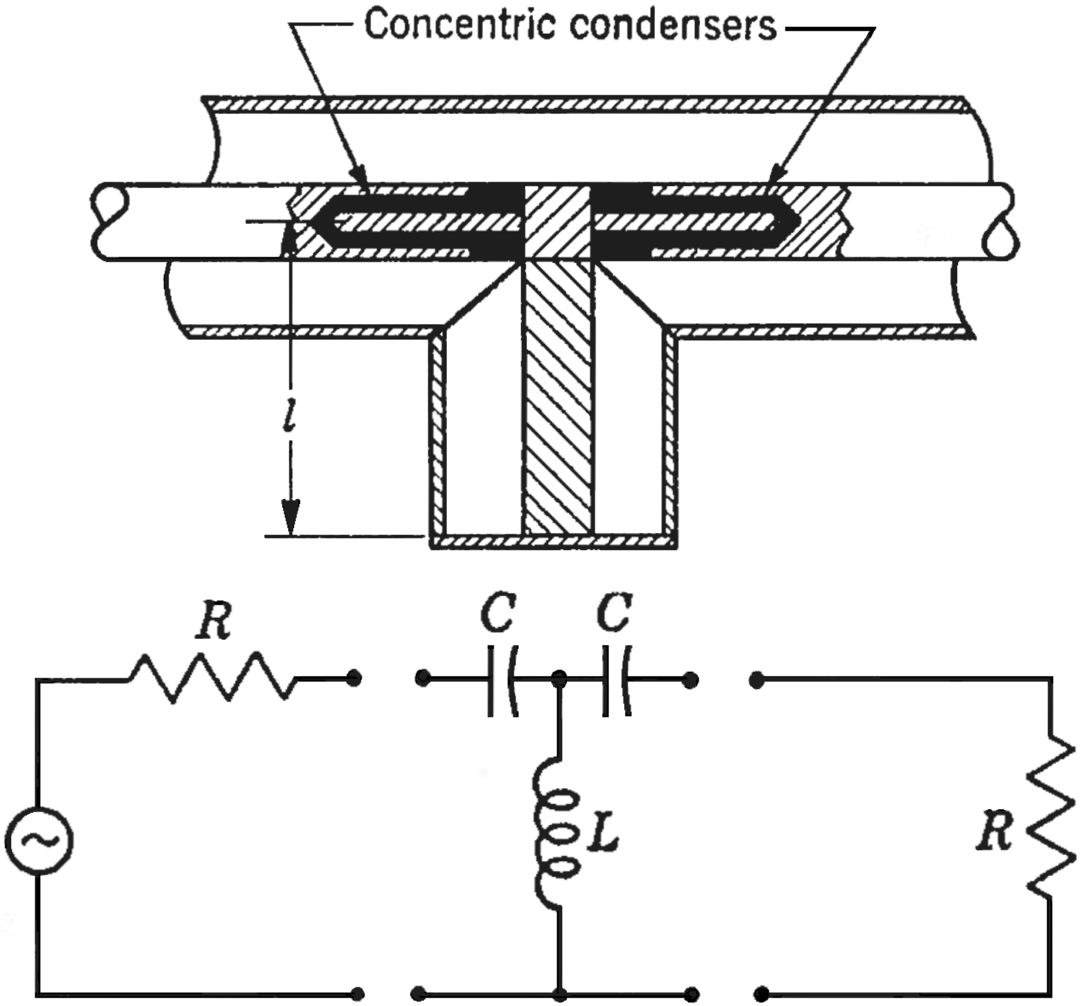
Re-Entrant Filter – Type 2

- **Introduced by S.B. Cohn**
- **Concentric, coaxial implementation of series stubs**
- **Example: Low-pass filter**



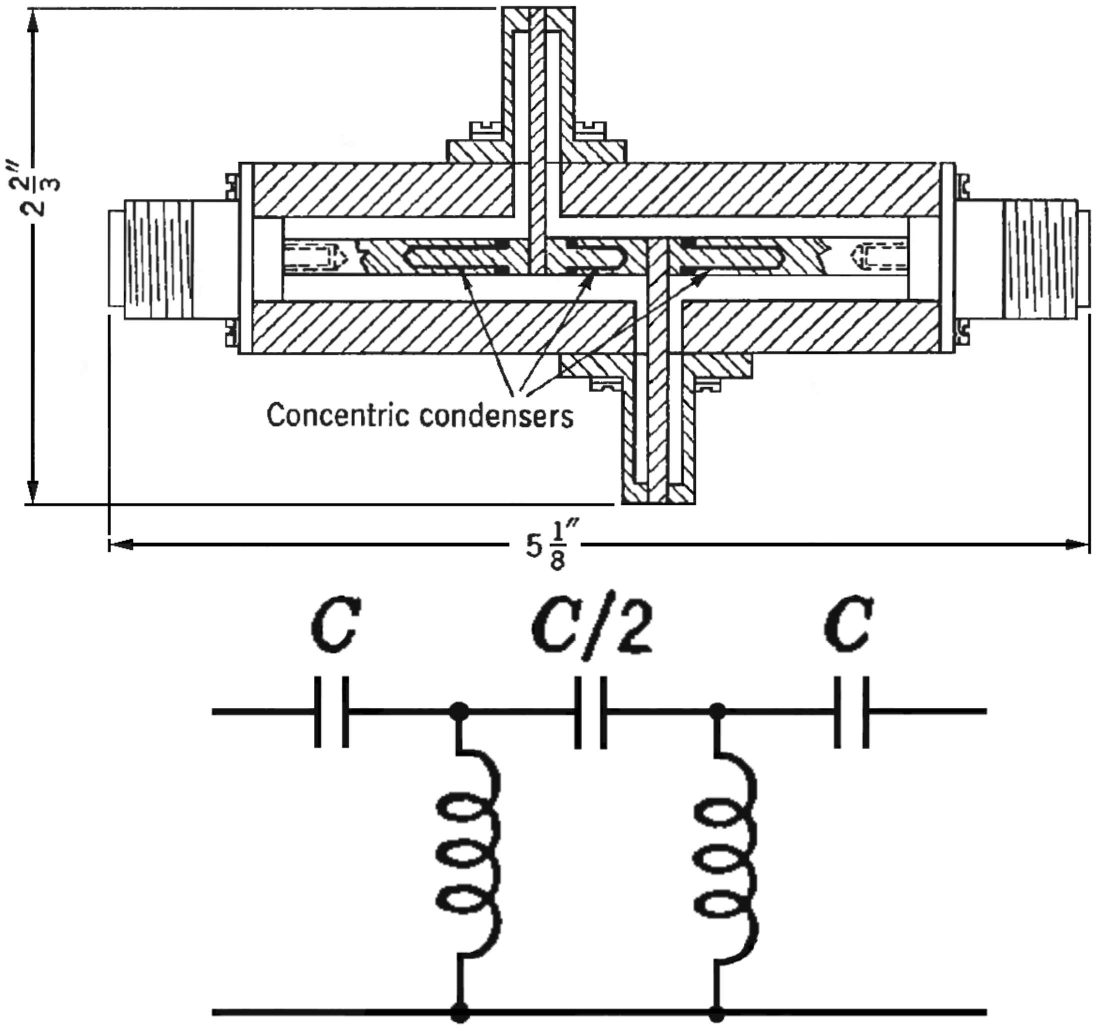


High-Pass Filter



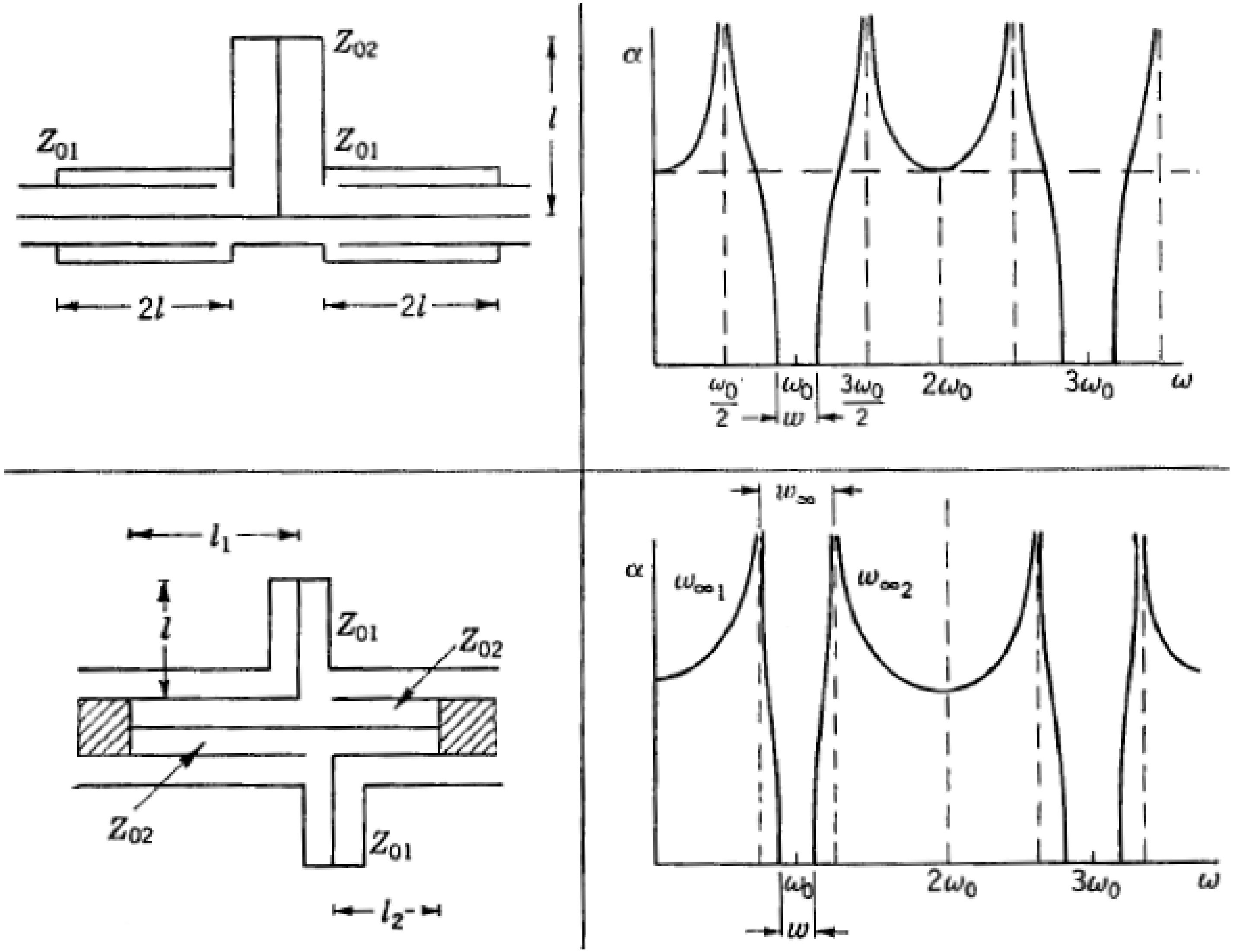
G.L. Ragan, ed., *Microwave Transmission Circuits*, McGraw-Hill, 1948

2-Stage High Pass Filter

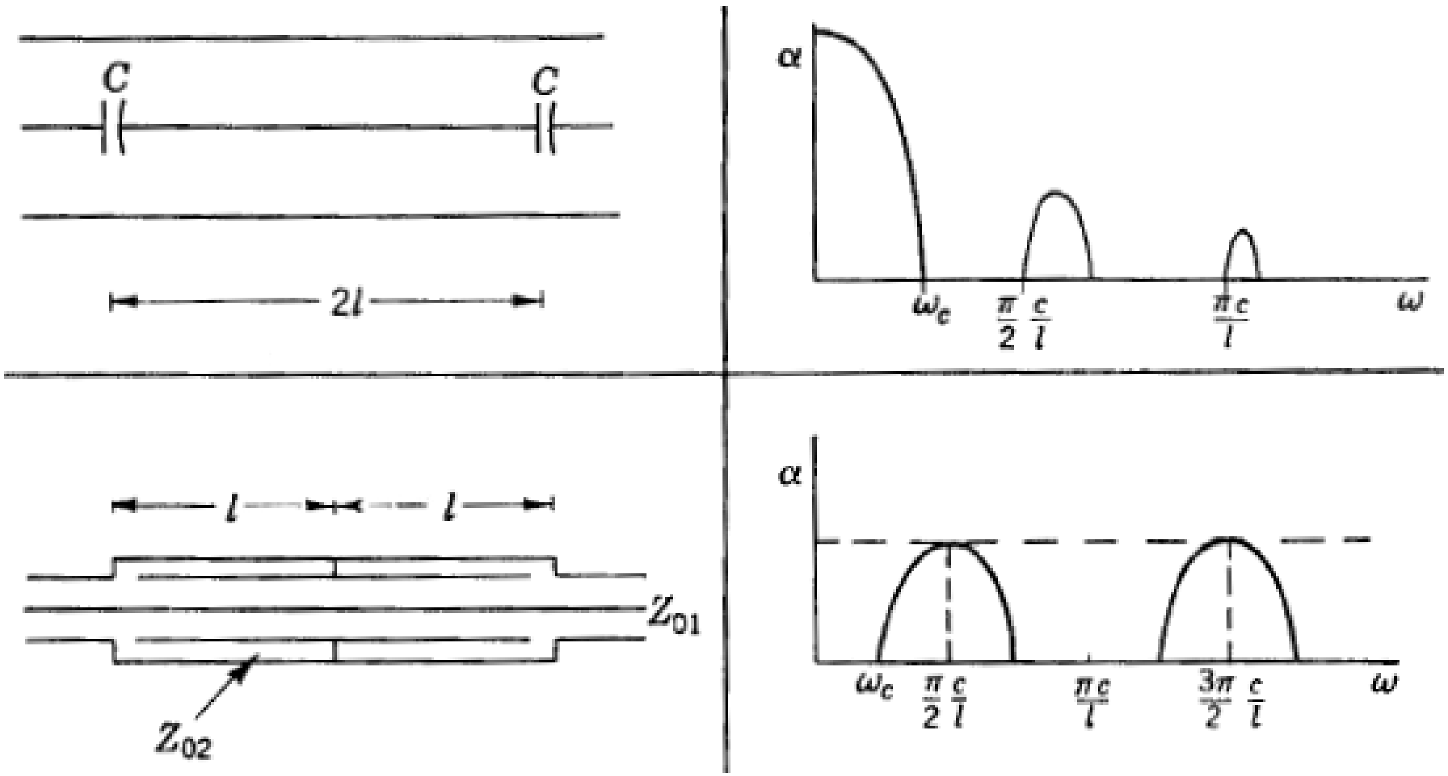


G.L. Ragan, ed., *Microwave Transmission Circuits*, McGraw-Hill, 1948

More Examples



More Examples



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The End

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