Ferrite Core Antenna Transformer Efficiency

-Characteristics

-Measurements

-Some Observations

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AI6XG

Today’s Adventure

- You Will Learn:
  - a Bit About Me
  - What is Different About Ferrite Cores
  - How This Affects Transformers
  - Two Methods to Measure Transformer Efficiency/Loss
  - What Affects Transformer Loss Measurements
- And You Will See:
  - Examples of Transformer Loss Measurements
  - Nice Photos From Mountain Summits

AI6XG

- First Licensed in 1973
  - License Lapsed in late 1980s
  - New Ticket in 2017
    - Thank you Bay Area Maker Faire!

- Primary Operation is HF CW
  - Summits on the Air (SOTA)

What is Summits On The Air?

- Operation from Mountain Tops
  - Pack in equipment
  - Portable power
  - QRP Radios

SOTA Antennas

- Lightweight
- Compact
- Efficient
- Easy to Assemble in Varying Conditions and Environments

Below and Above Tree Line

Anytime of the Year

Courtesy of KE6MT

End Fed Half Wave (EFHW)

- Popular SOTA Antenna
- Lightweight and Compact

End Fed Half Wave (EFHW)

- Several Configurations
  - Sloper
  - Inverted Vee
  - Inverted L

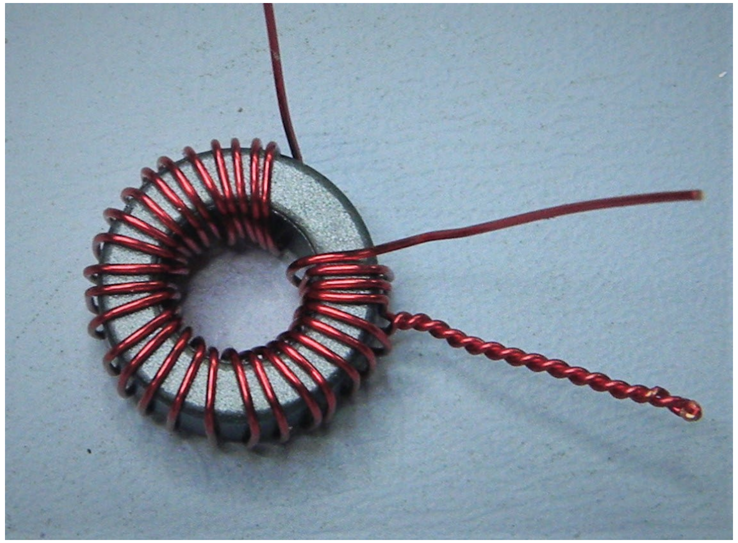
End Fed Half Wave (EFHW)

- Multiband
- Resonant
- No Tuner Required


Very Short Feedline

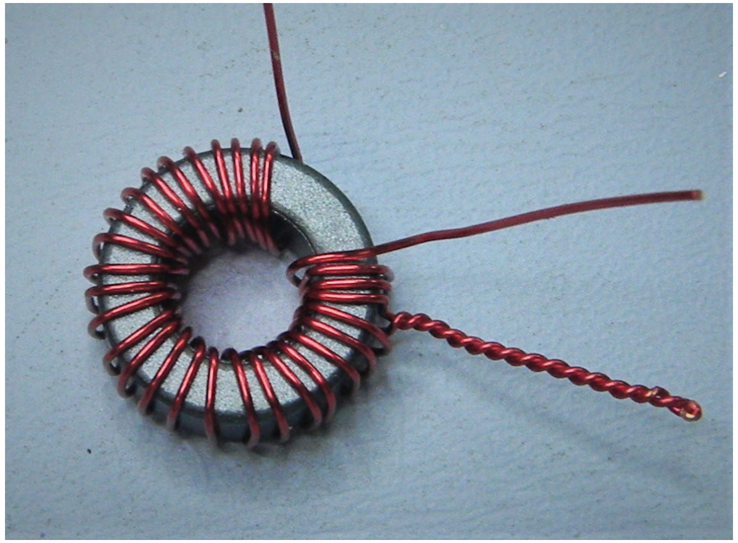

No Feedline!
Courtesy of K6ARK Portable Radio

EFHW Transformer



- Transform from High Z at Feedpoint
  - 49:1, 64:1, 81:1
- Ferrite Core Used
- Insertion Loss
  - Am I Losing Power?
  - Measured with VNA S21
  - nanoVNA

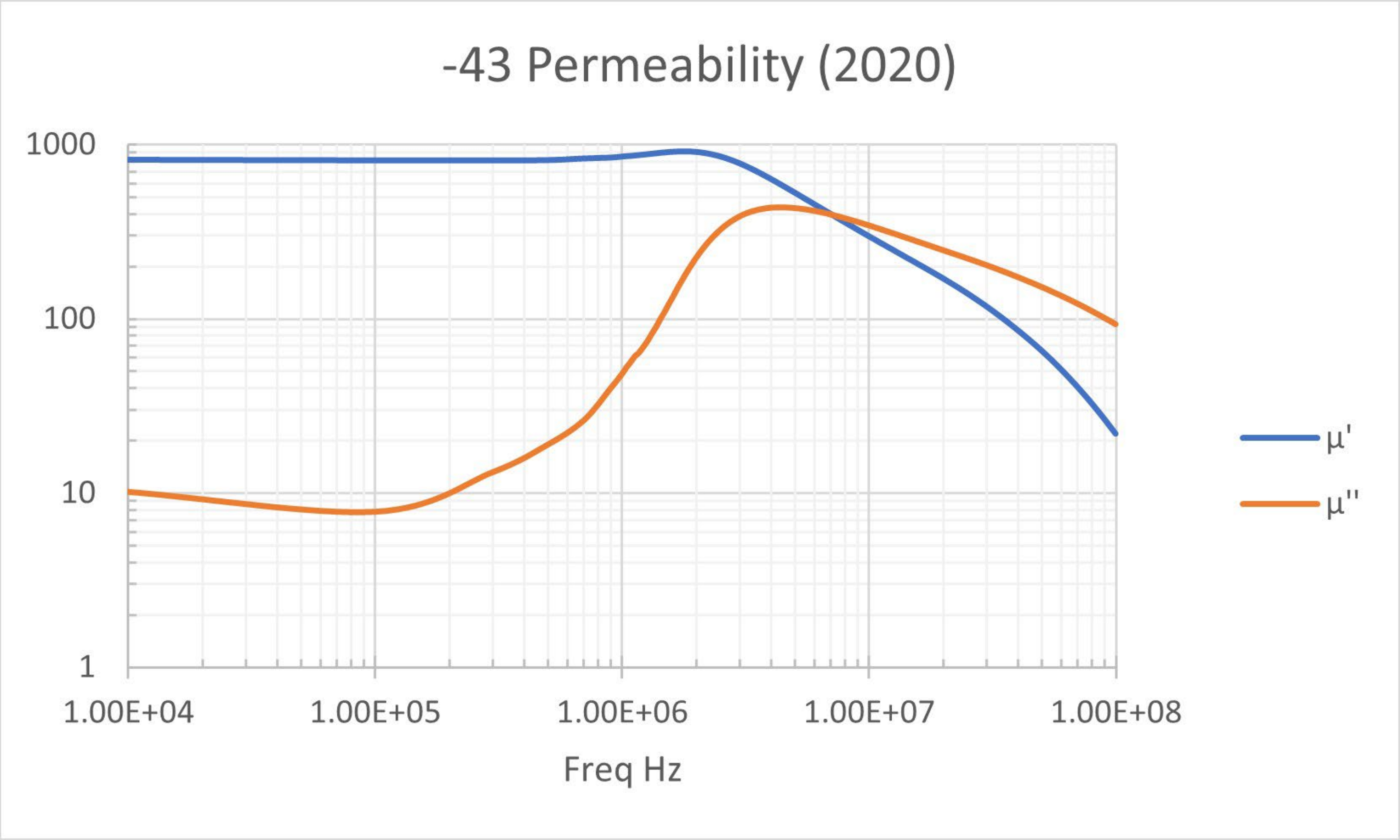
EFHW Transformer



- Why use a Ferrite Core?
  - High Permeability
  - Wide Bandwidth
  - Powered Iron Cores Not Used
- Which Cores Are Used?
  - FT50-43 toroid popular for QRP
  - FT240-43 toroid popular for QRO

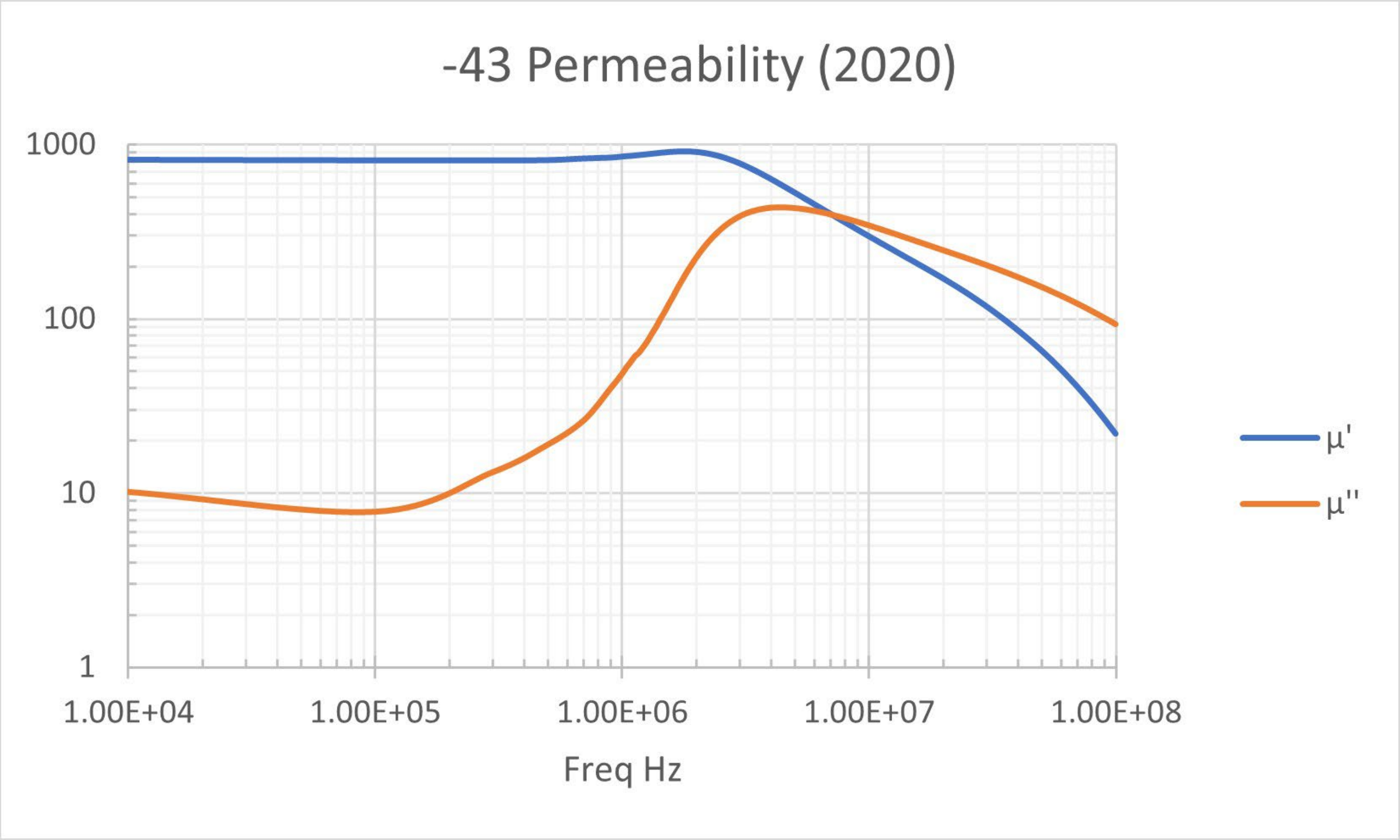
Complex Permeability

- Two Elements
  - μ' Inductive
  - μ'' Resistive
- Varies with Frequency



Complex Permeability

- Resistive Element
  - μ''
  - Power loss – Heat!
  - Core Loss



Inductance and Impedance

- Inductance for N Turns

$$L = N^2 \frac{\mu A_{xc}}{2\pi r}$$

- A_l Specified by Manufacturer
  - Depends on Core Characteristics
  - Measured at 10kHz

$$A_l = \frac{\mu A_{xc}}{2\pi r}$$

A_{xc} is cross sectional Area
r is core radius
μ is permeability

Inductance and Impedance

- Online Inductance Calculators Use A_l
  - Okay for Powered Iron Cores

$$L = N^2 A_l$$

- Not for Ferrite Cores!
  - μ is Complex
  - μ Varies with Frequency
  - μ_i ~ 800 for -43
  - μ_i ~ μ' at Low Frequencies

$$A_l\left(\frac{\mu' - j\mu''}{\mu_i}\right)$$

Inductance and Impedance

- Calculate Impedance

$$Z = j2\pi fL$$

- Adjust for Complex Permeability

$$Z = j2\pi fN^2A_l\left(\frac{\mu' - j\mu''}{\mu_i}\right)$$

- Real and Imaginary Parts

$$Z = 2\pi fN^2A_l\left(\frac{\mu''}{\mu_i}\right) + j2\pi fN^2A_l\left(\frac{\mu'}{\mu_i}\right)$$

Inductance and Impedance

- Imaginary is Reactance

$$X = 2\pi f N^2 A_l \left(\frac{\mu'}{\mu_i} \right)$$

$$L = N^2 A_l \left(\frac{\mu'}{\mu_i} \right)$$

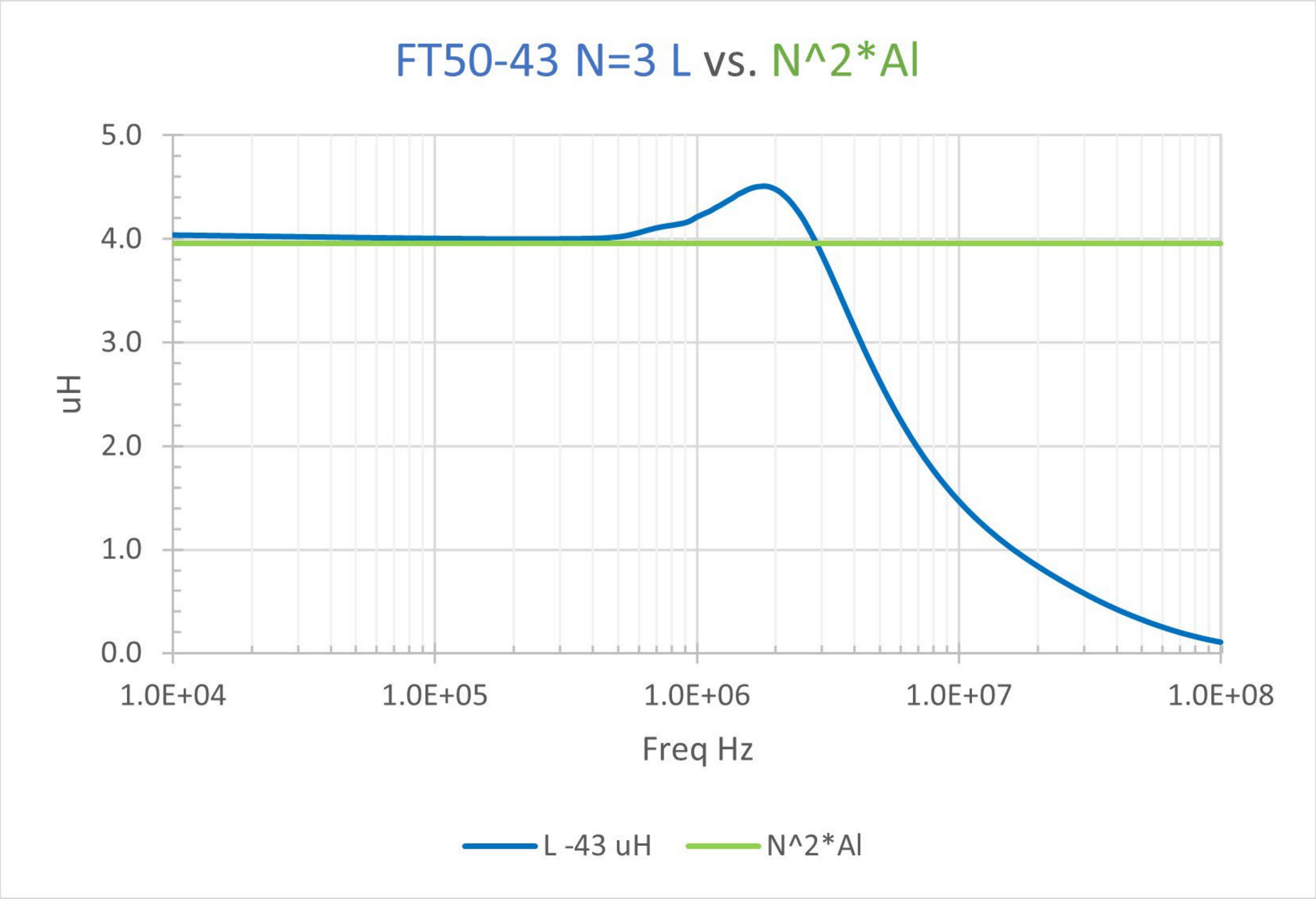
- Real is Resistive
  - Dissipates Power
  - Core Loss

$$R = 2\pi f N^2 A_l \left(\frac{\mu''}{\mu_i} \right)$$

Inductance vs. Frequency

$$L = N^2 A_l \left(\frac{\mu'}{\mu_i} \right)$$

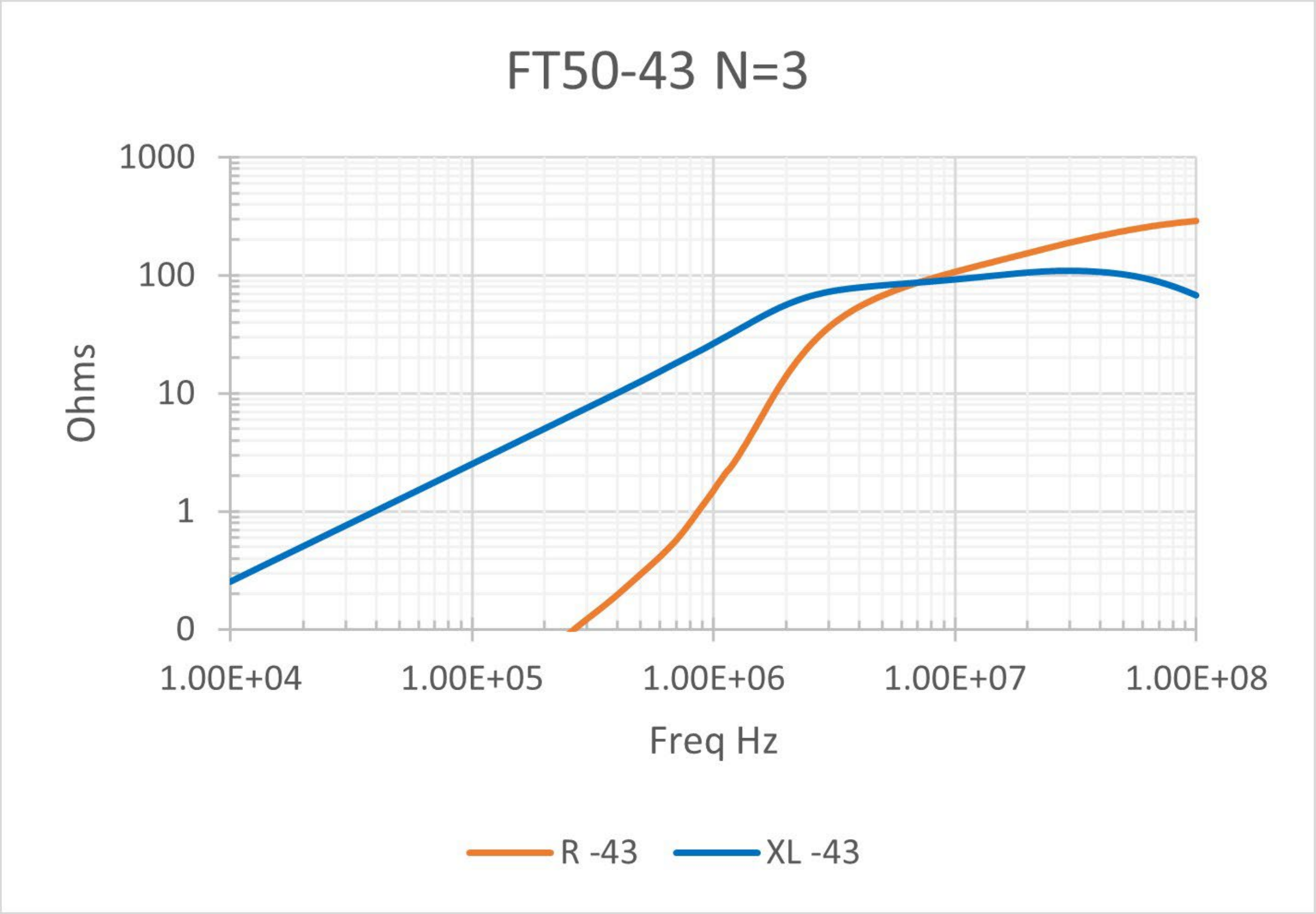
- A_l Specified by Manufacturer
- A_l ~ 440 FT50-43
- μ_i ~ μ' at Low Frequencies



Resistance vs. Frequency

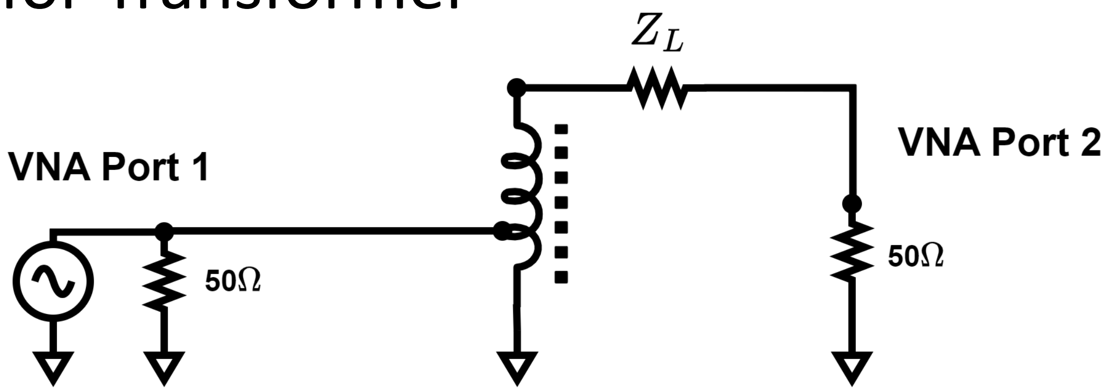
$$R = 2\pi f N^2 A_l \left(\frac{\mu''}{\mu_i} \right)$$

- Becomes Significant at High Frequencies

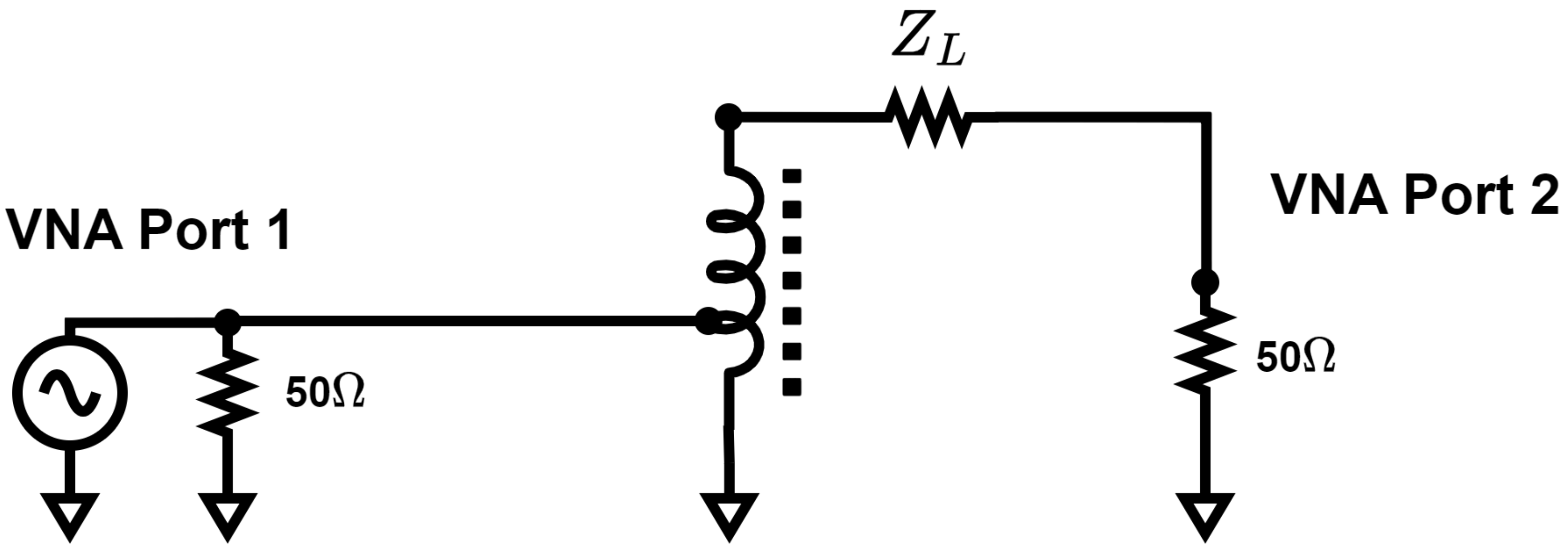


Measuring Transformer Loss

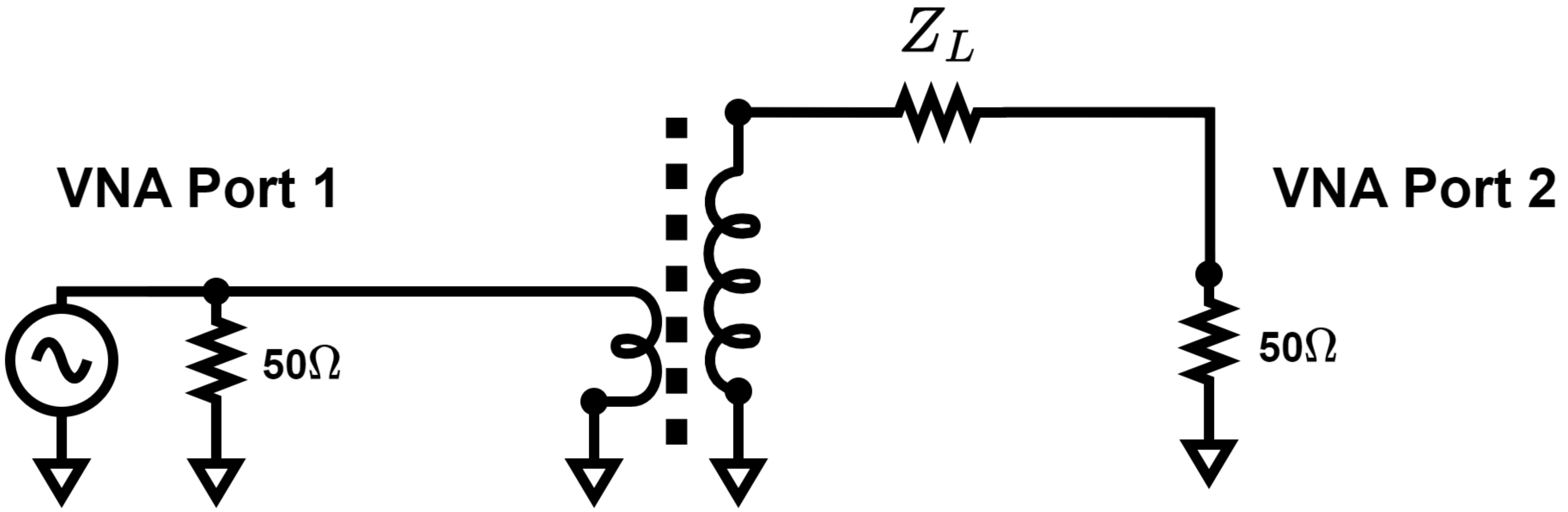
- First Method
- Single Transformer with Resistor Load
    - Resistor plus 50Ω Port 2 Impedance
    - 'Antenna' Load for Transformer



Tapped Transformer

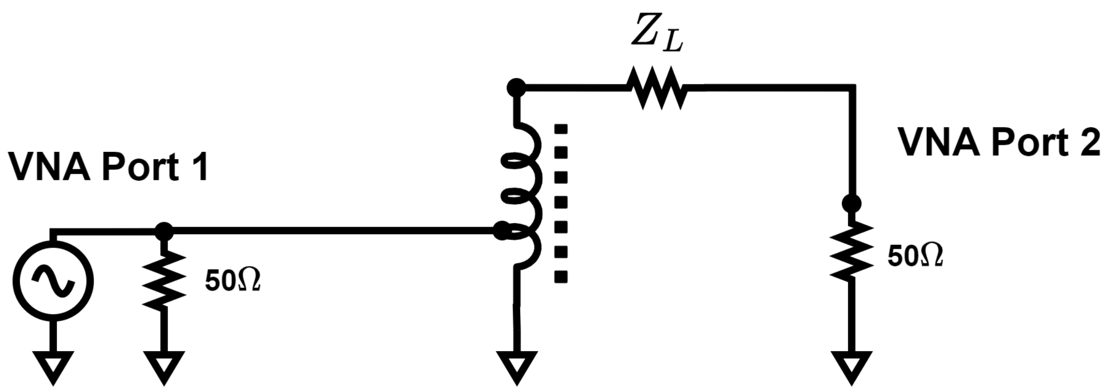


Linked Transformer



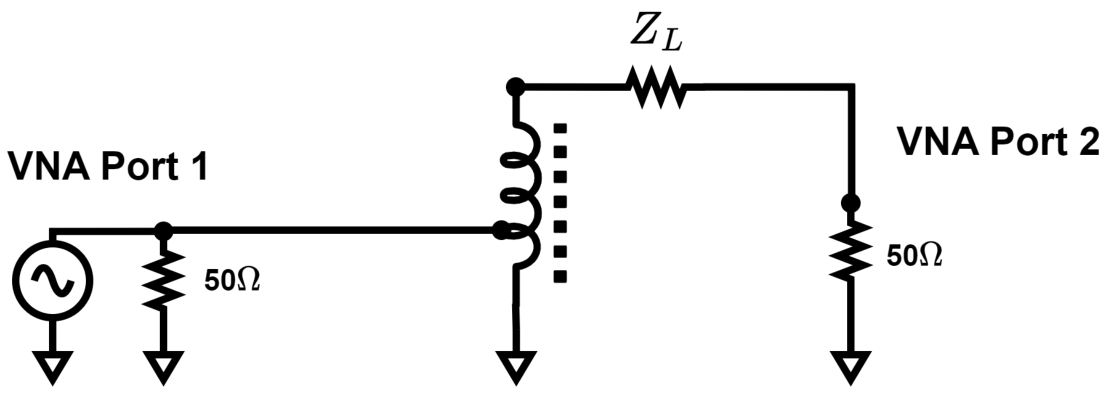
Measurement Parameters

- VNA Measures ‘Insertion Loss’
  - $S_{21} = V(\mathrm{port2})/V(\mathrm{port1})$
- Load Resistor Z_L
  - 2400Ω for 1:49
  - 4000Ω for 1:81

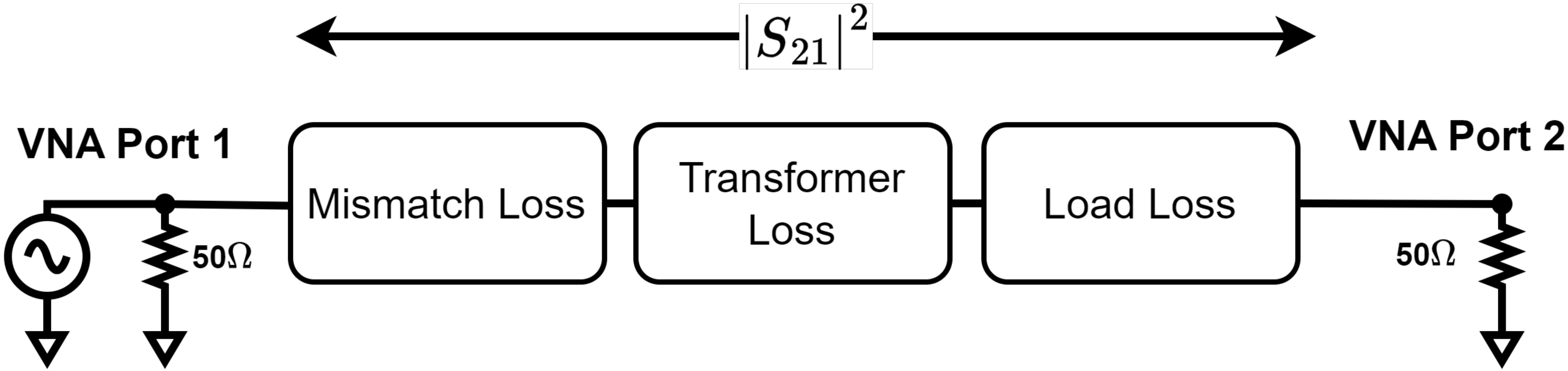


Measurement Parameters

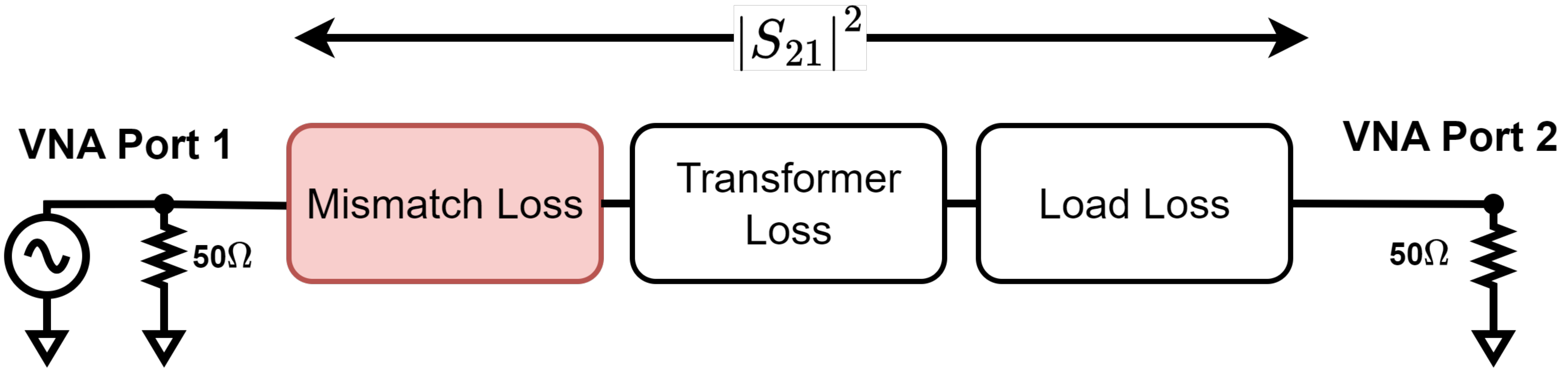
- Transformer Loss
  - Power Loss in dB
  - Efficiency Equivalent
  - $\text{eff}(\%) = 100 \times 10^{-(\text{xfmr}_{loss}(dB)/10)}$



Insertion Loss

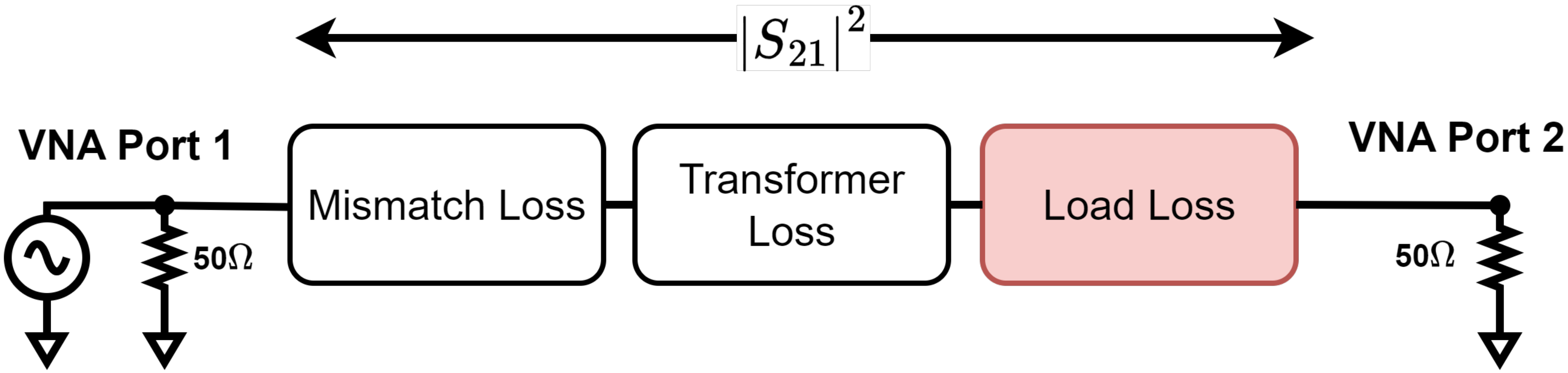


Mismatch Loss



$$MM_{loss}(dB) = -10\log\left(1 - |S_{11}|^2\right)$$

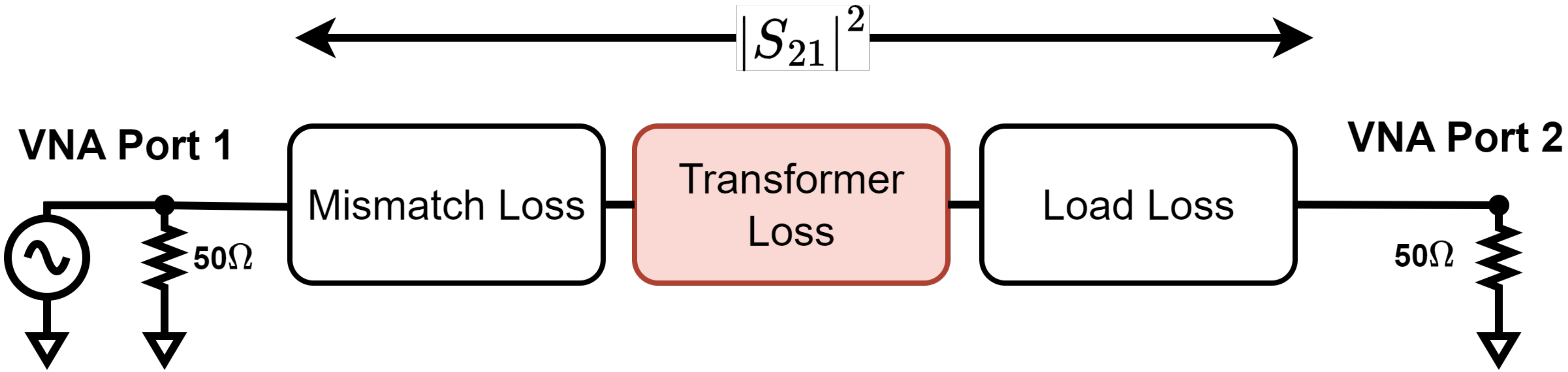
Load Loss



- Series Measurement of Z_L as a Complex Impedance
  - Separate Measurement – Don't Assume a Pure Resistance

$$Load_{loss}(dB) = 10\log\left(|S_{21}(Z_L)|^2 / \left(1 - |S_{11}(Z_L)|^2\right)\right)$$

Transformer Loss



- Transformer Loss

$$\text{xfmr}_{loss}(dB) = 10\log\left(|S_{21}|^2\right) - MM_{loss}(dB) - Load_{loss}(dB)$$

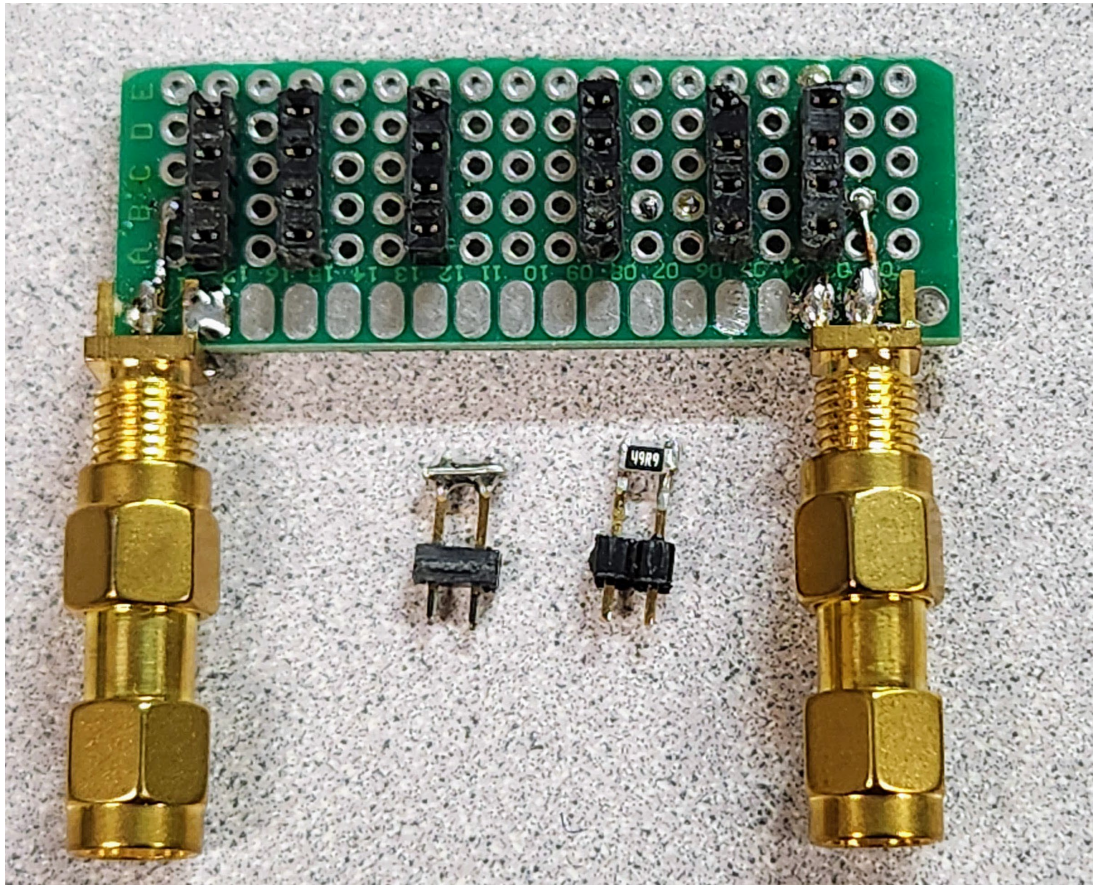
Measuring Transformer Loss

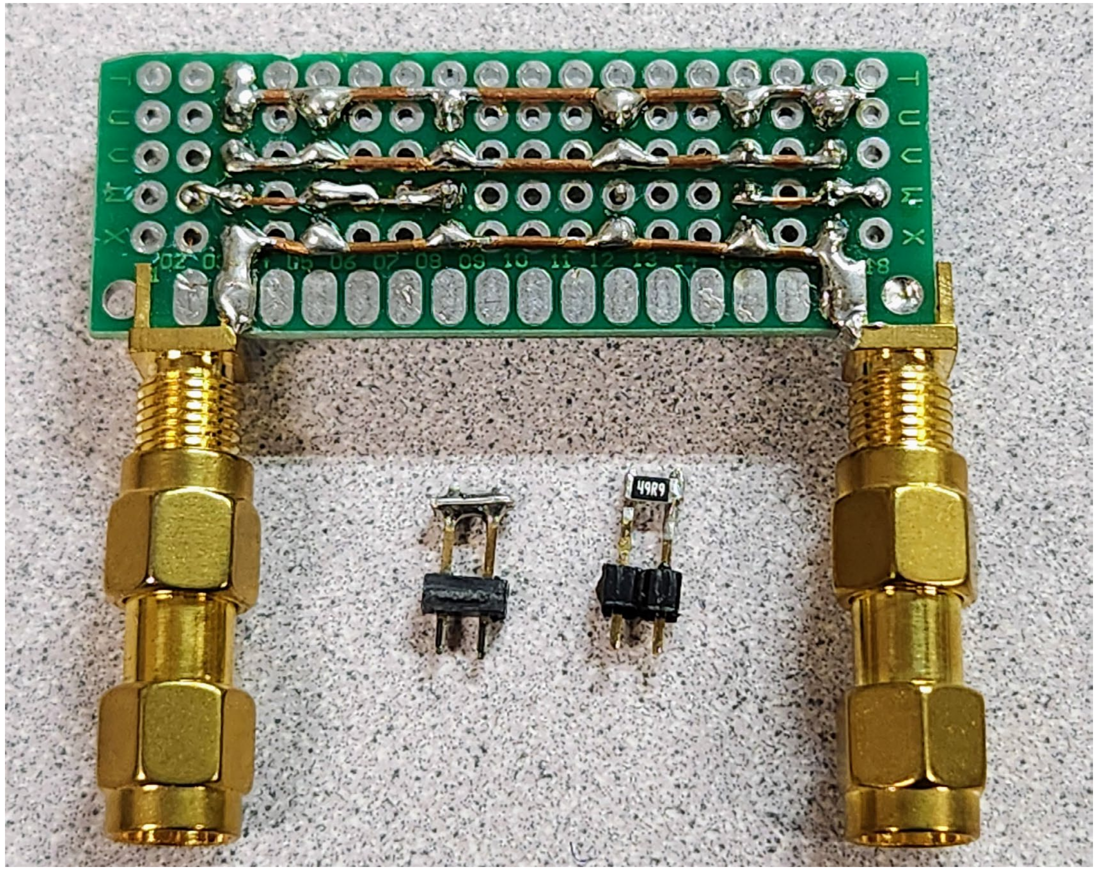
- Use nanoVNA With a Test Fixture
  - Recommend Idle for > 15 minutes
- Calibrate nanoVNA and Test Fixture
  - Open, Short, Load, Isolate, Through
  - Over Test Frequency Range

Measuring Transformer Loss

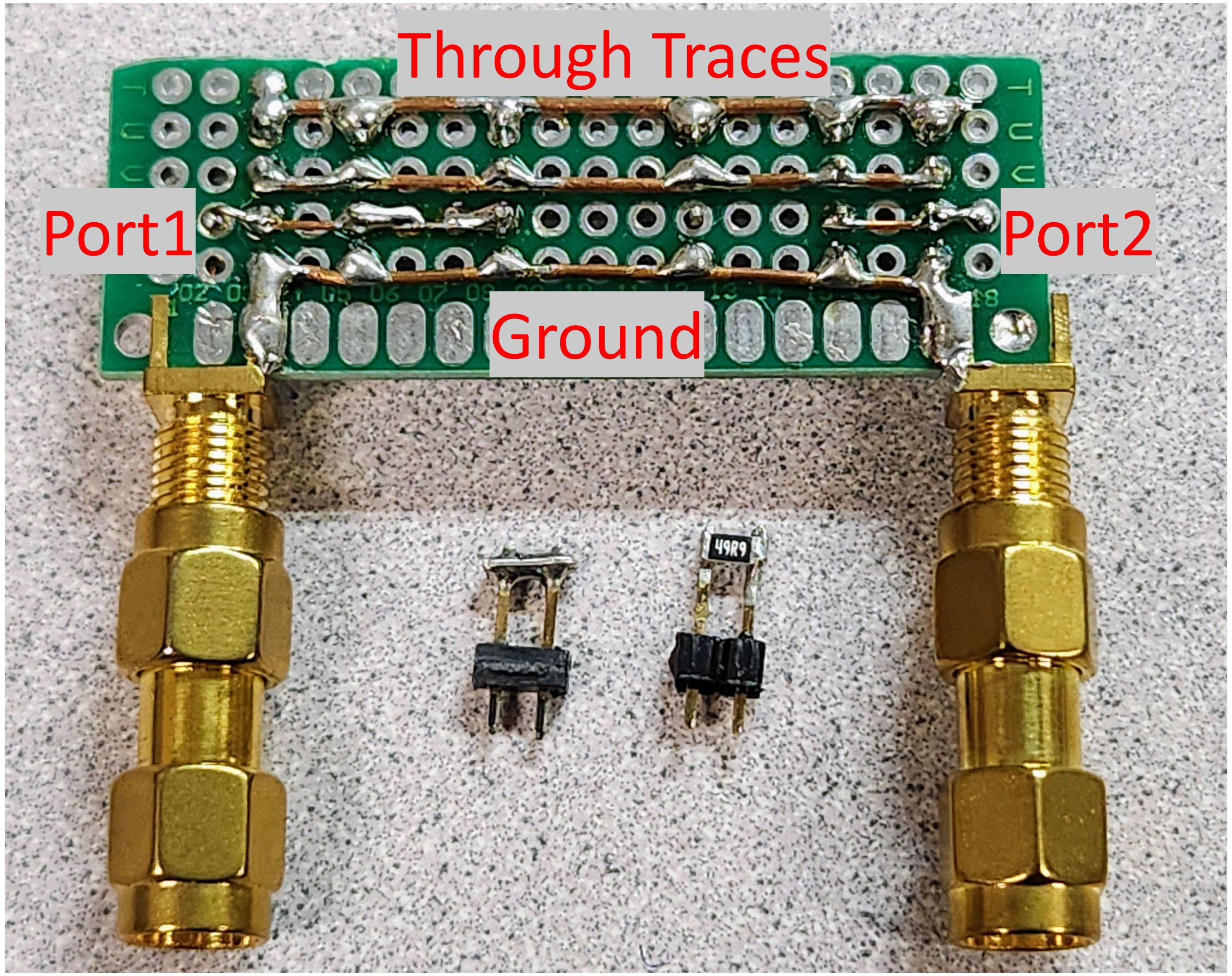
- Use Test Fixture
  - Better Repeatability
  - Connect Directly to NanoVNA
  - Part of Test Calibration
  - Direct Ground Connection Between Ports
  - Headers for Configuration Change

Test Fixture

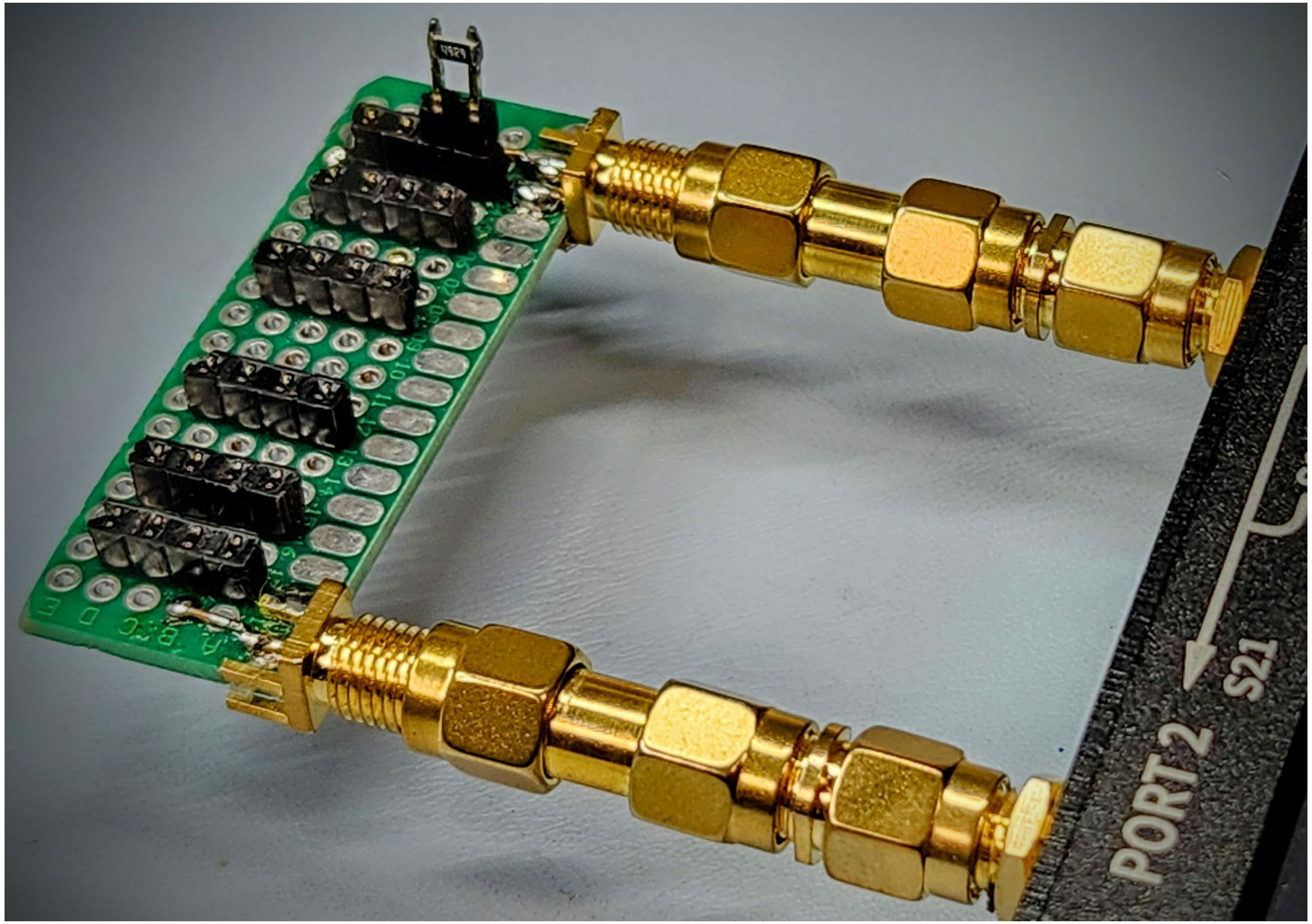




Test Fixture



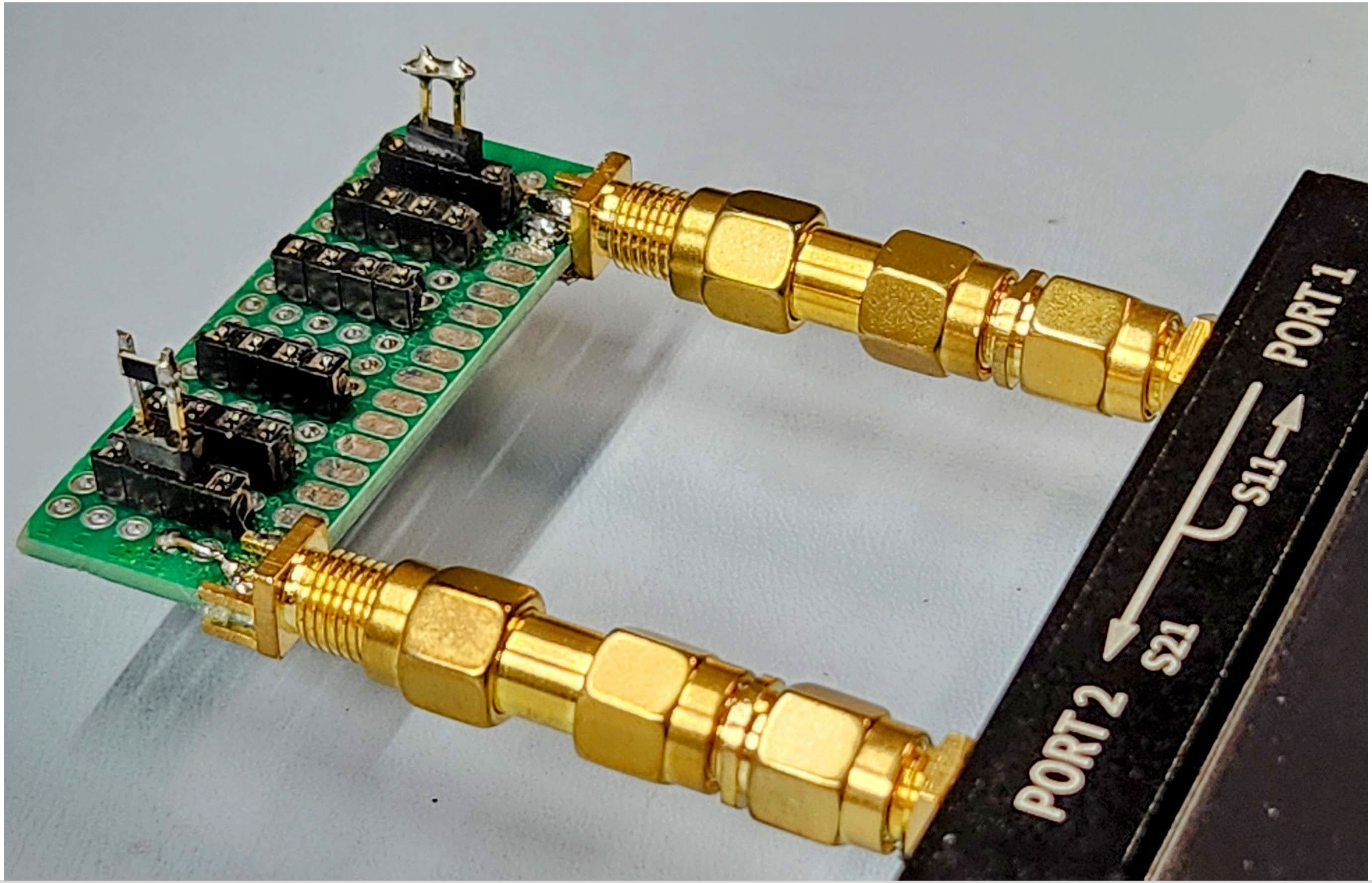
50 Ohm Load Port1 Calibration



Measuring Transformer Loss

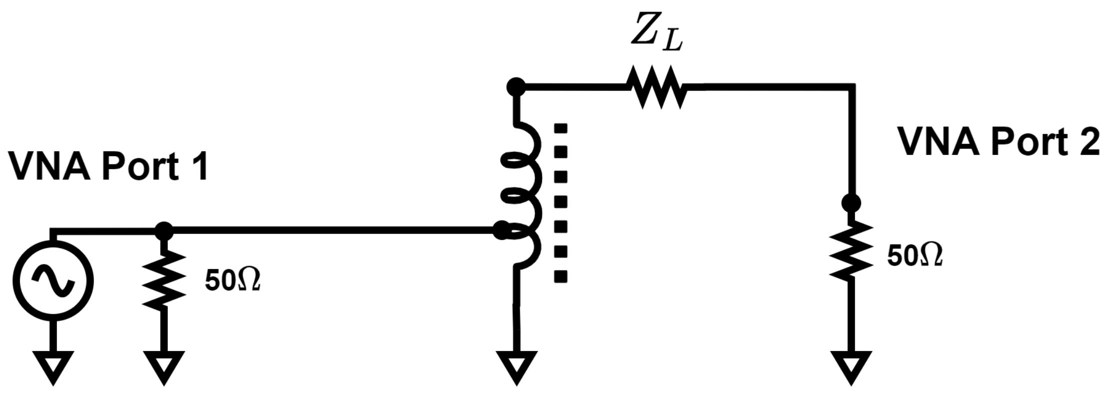
- Measure Load Resistor In Test Fixture
  - Over Test Frequency Range
  - Series Through Measurement
  - Load S2P (F S11 S21 R I) Data into Spread Sheet
  - https://github.com/phase2682/FC-XFMRS-AI6XG

Load Resistor Characterization

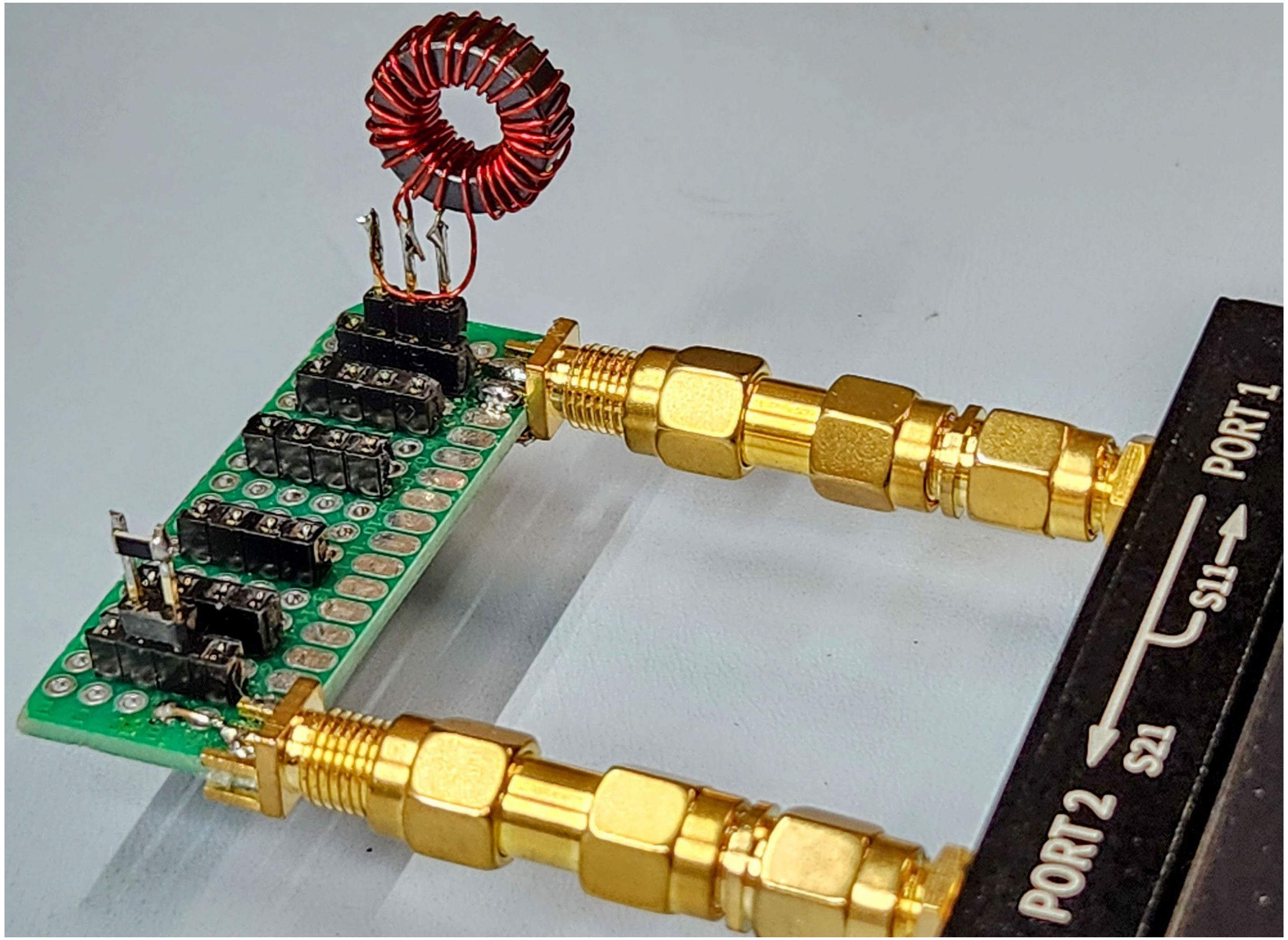


Measuring Transformer Loss

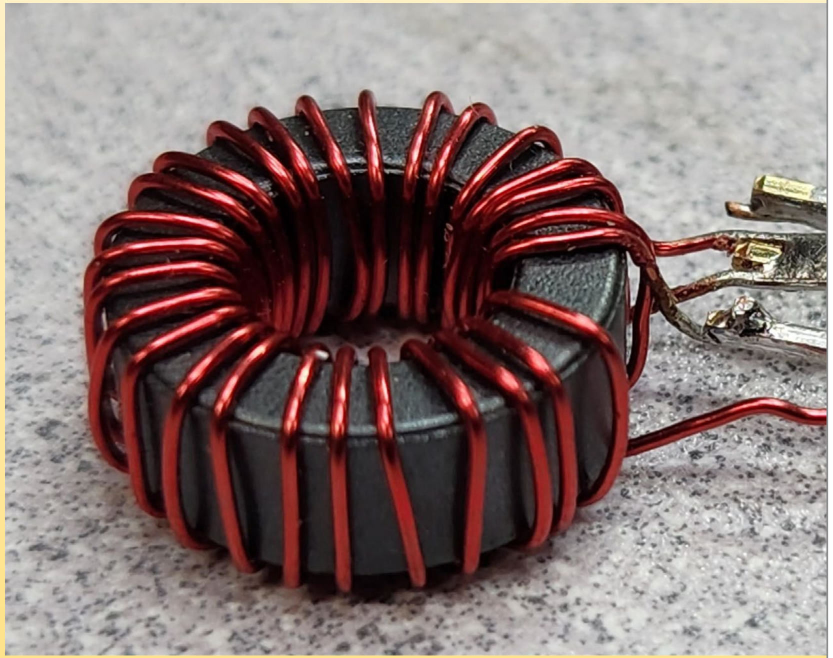
- Put Transformer and Load Resistor in Test Fixture
  - Test Circuit Configuration
  - Load S2P (F S11 S21 R I) Data into Spread Sheet
  - Calculate Transformer Loss

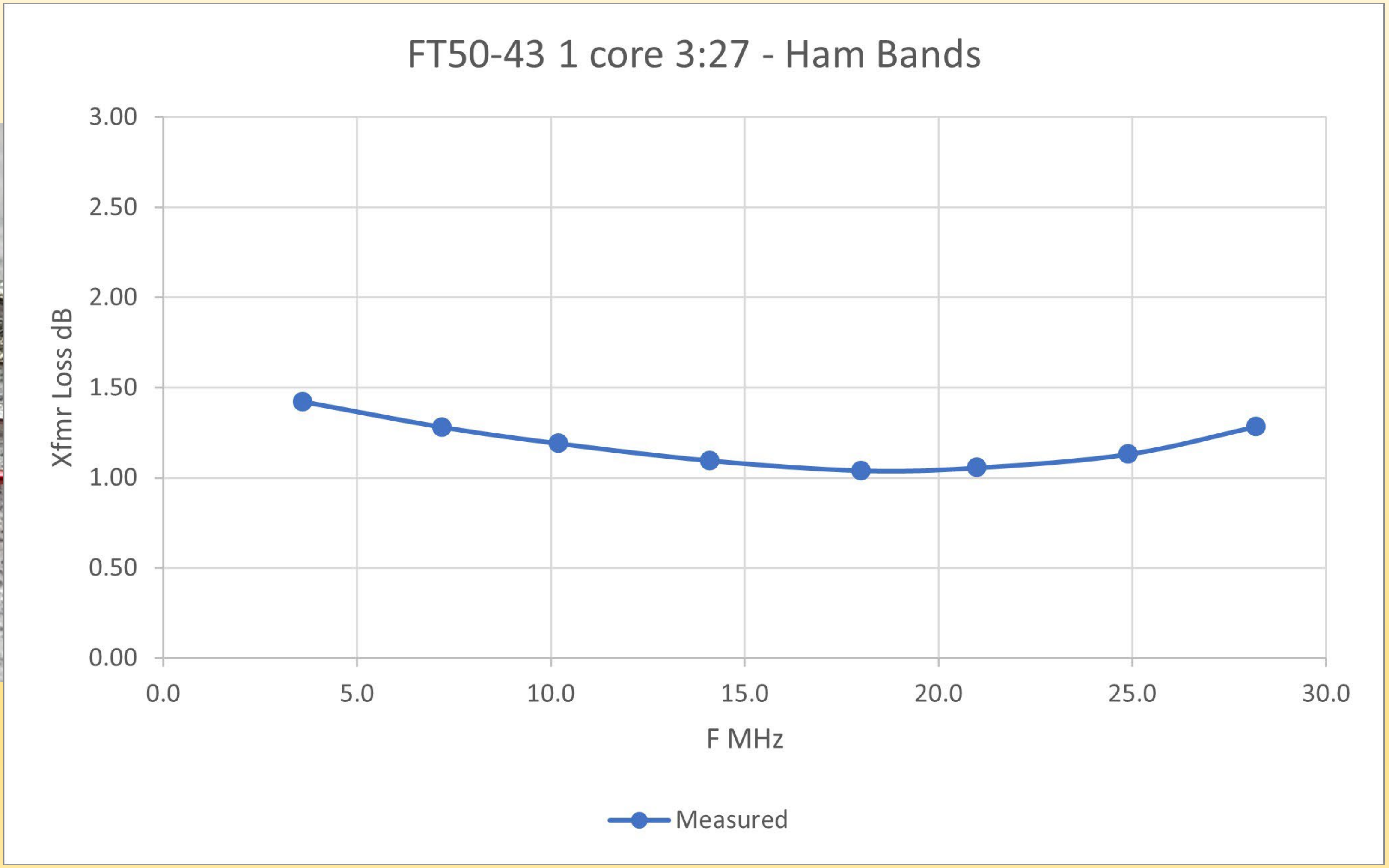


Measuring Transformer Loss

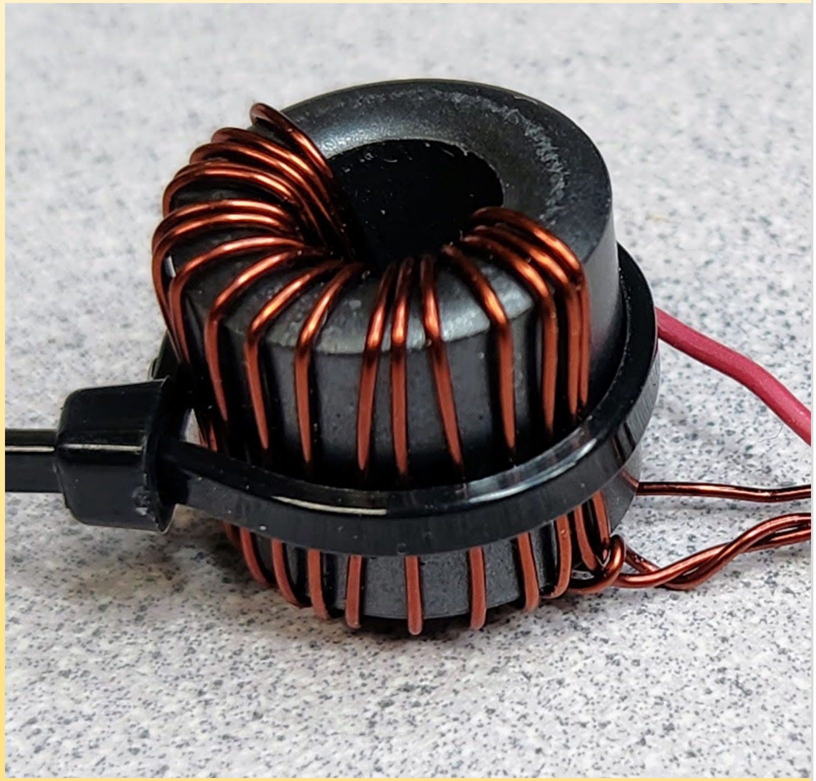


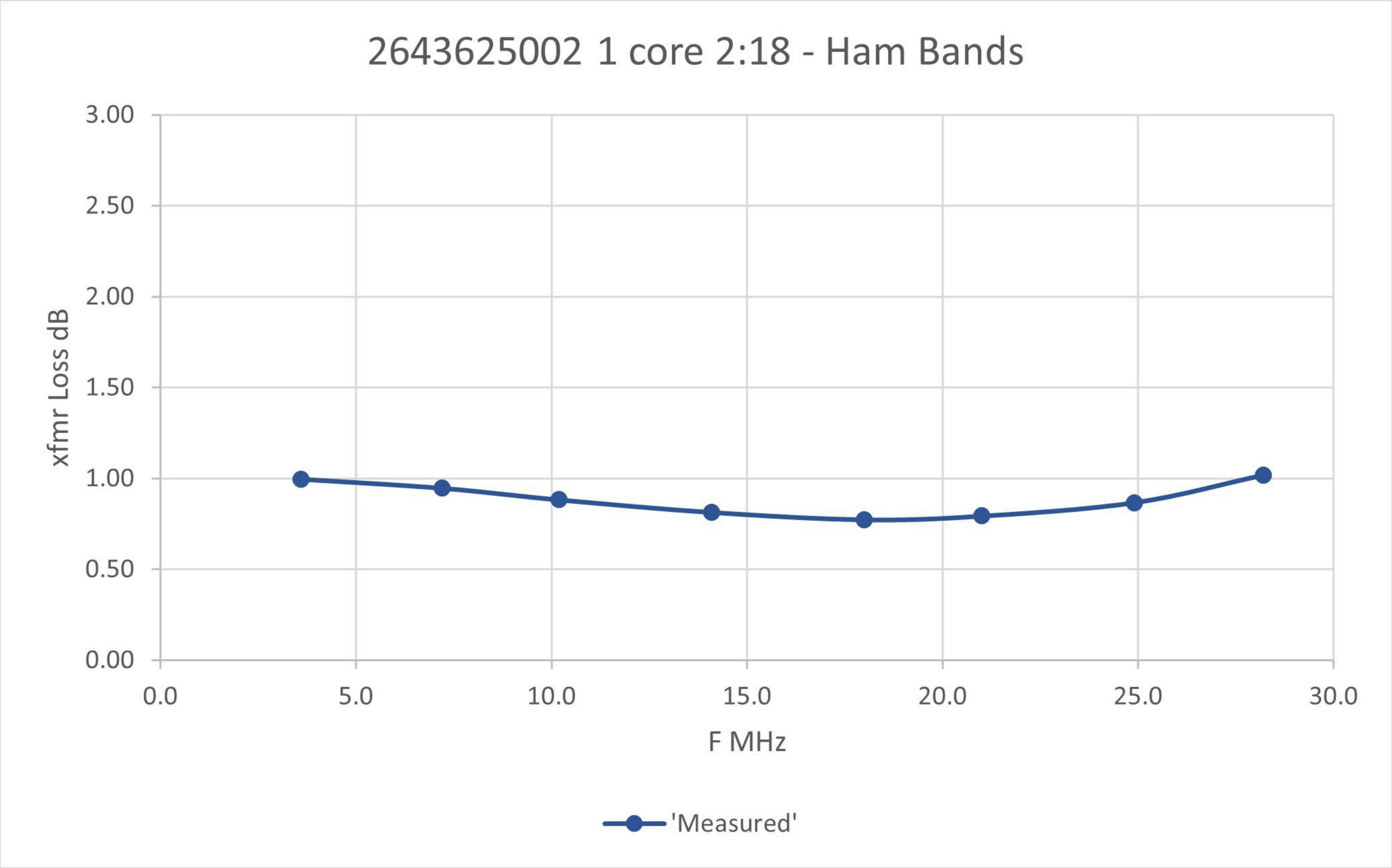
FT50-43 3:27 SOTA Transformer



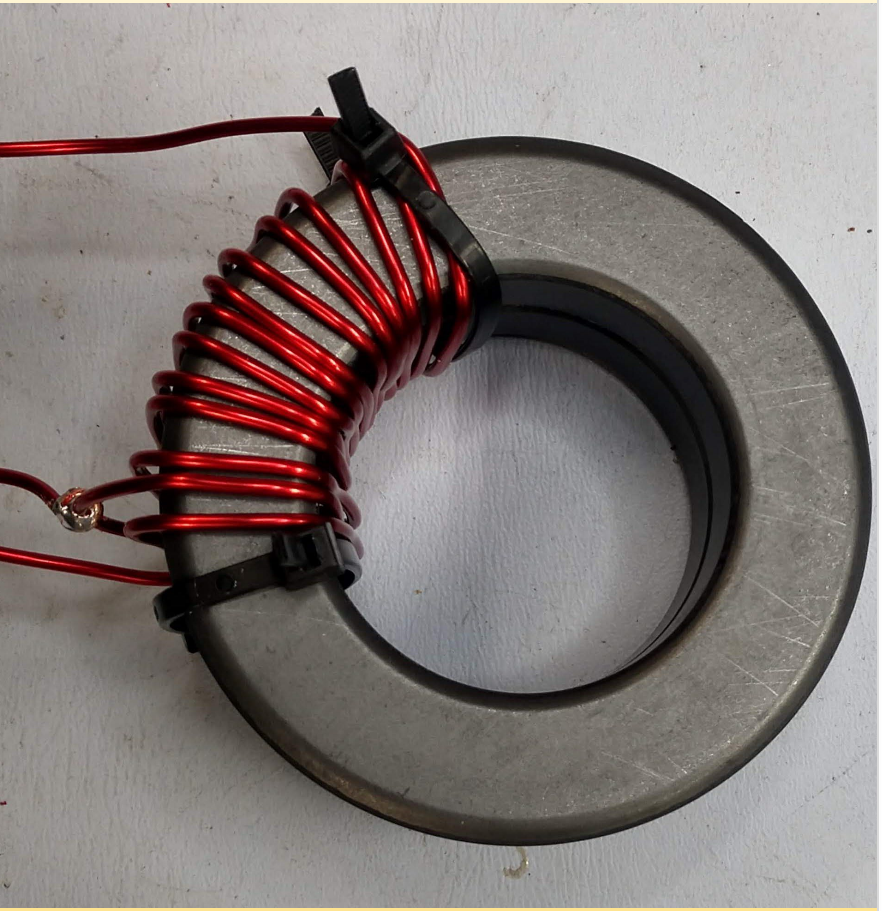


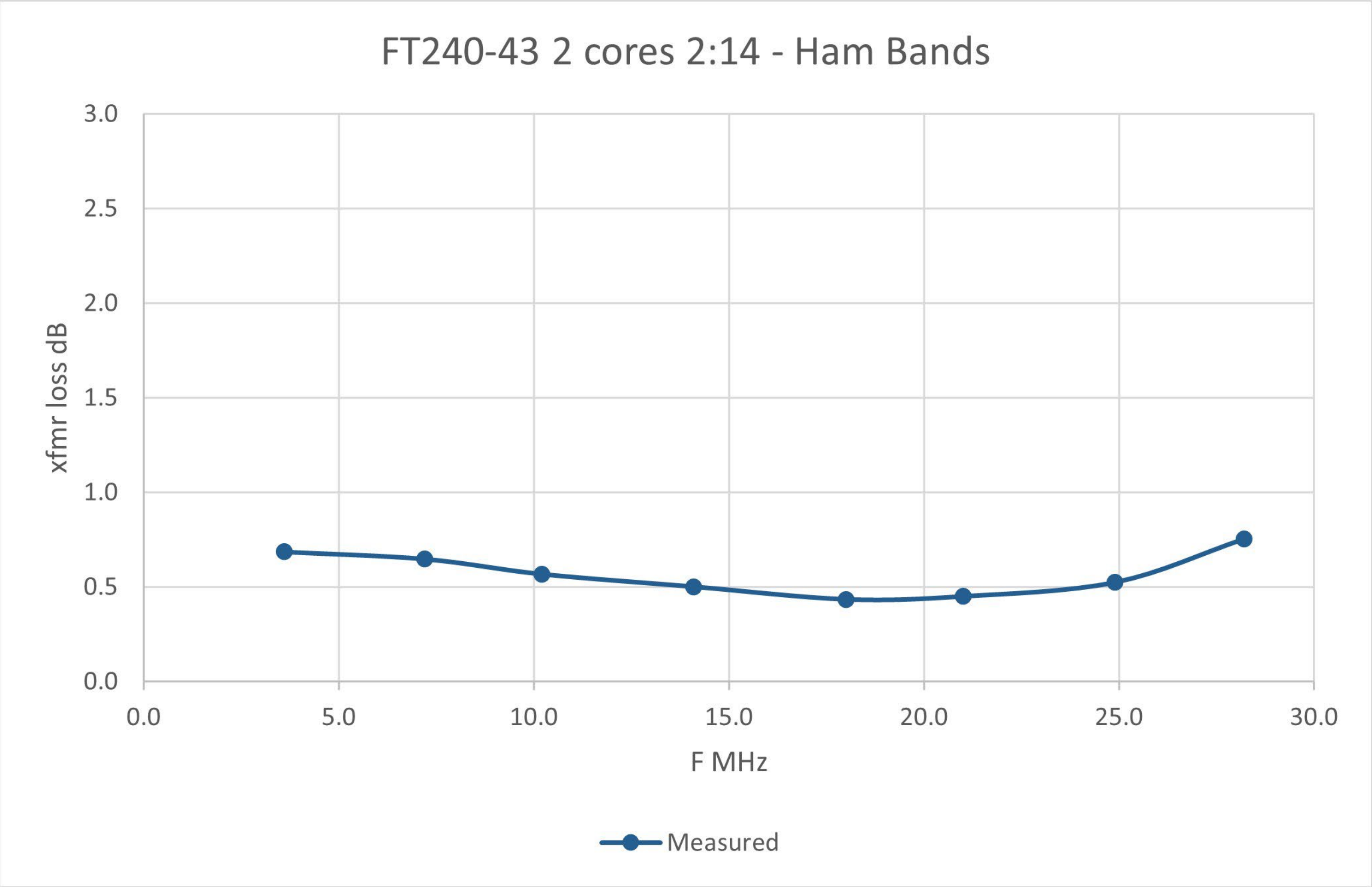
2643625002 2:18 SOTA Transformer





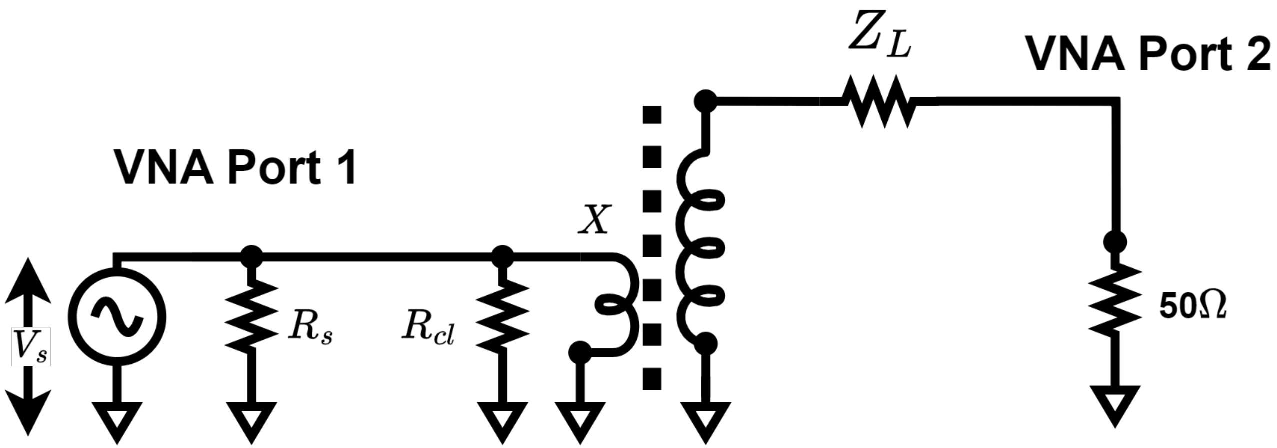
FT240-43 2:14 2 Cores QRO Transformer





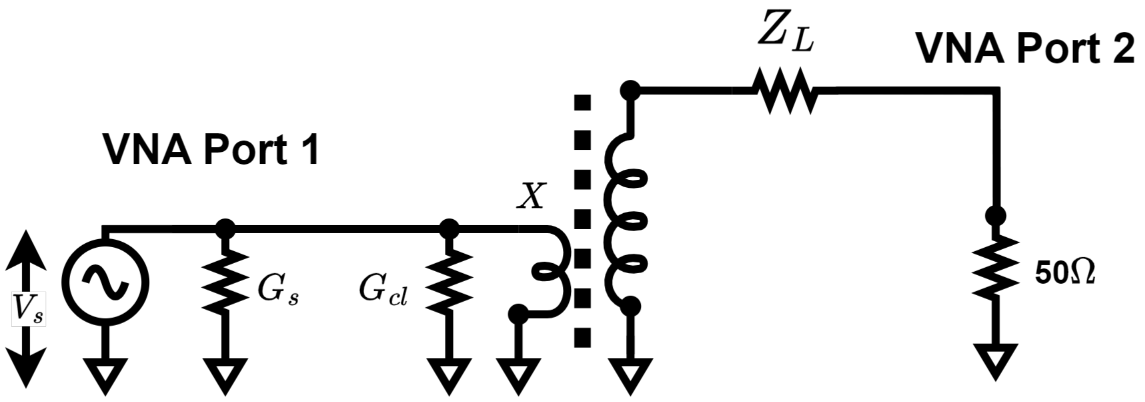
Estimate Transformer Loss

- Core Loss as an Estimate
  - X and R in Transformer
- Source Power
  - V_s^2/R_s
- Power Loss in Rcl
  - V_s^2/R_{cl}



Estimate Transformer Loss

- Use Conductance
  - $V_s^2 G_s \quad V_s^2 G_{cl}$
- Power Out of Transformer
  - $V_s^2 G_s - V_s^2 G_{cl}$
- Efficiency
  - $(V_s^2 G_s - V_s^2 G_{cl}) / (V_s^2 G_s) = 1 - G_{cl}/G_s$
  - $\mathrm{Core}_{loss}(dB) = -10 \log(1 - G_{cl}/G_s)$



Estimate Transformer Loss

- To Determine Conductance for Transformer
  - Calculate Z First
  - $Z = 2\pi f N^2 A_l \left(\frac{\mu''}{\mu_i}\right) + j2\pi f N^2 A_l \left(\frac{\mu'}{\mu_i}\right)$
  - Then Calculate 1/Z = Y as a Complex Number
    - $1/(a + jb) = (a - jb)/(a^2 + b^2)$
  - Y is Admittance
  - Conductance is Real Portion of Y
  - N is Primary Turns

Estimate Transformer Loss

- Excel Spread Sheet Available
  - FT50-43, FT240-43, 2643625002
- Permeability, Dimensions
- Input Freq, N turns, # of cores
- Calculates:
  - Z, Y, L
  - Efficiency %,
  - Loss(dB)

	Calculator for Fair-rite FT50-43 series		
	Physical dimensions from toroids.info		
number of cores	1		
Frequency (MHz)	7.2		
Outer Dia. (mm)	12.7	toroids.info	
Inner Dia. (mm)	7.15	toroids.info	
width/height (mm)	4.9	toroids.info	
μ'	394.5	auto fill for	
μ''	394.6	HF ham bands	
Turns	3		
Cs (pFd)	0		
			Σ
Al (nH)	222.10		ci
ΣA/l (m) flux crowding	0.0004480		Sr
	real	imaginary	Sr
Y (S)	0.005529	-0.005528	
Z (Ω)	90.5	90.4	
|Z| (Ω)	127.9		
Ls (μH)	1.999		
winding length (cm)(inch)	10.6	4.2	
winding length (cm)(inch)	12.8	5.0	
expected effeciency	72.4%		
expected loss dB	1.405		

Compare With Online Calculator

Inputs:

Frequency (MHz)	7.200
Al (nH)	440.0
μi	800.0
μ'	394.5
μ"	394.6
Turns	3.0
Cs (pF)	0.000

Calculate

Results:

ΣA/l (m)	0.0004377
Y (S)	0.00566-j0.00566
Z (Ω)	88.4+j88.3
|Z| (Ω)	125
Ls (μH)	1.95

https://owenduffy.net/calc/toroid2.htm Using A_L and μ_i

	Calculator for Fair-rite FT50-43 series	
	Physical dimensions from toroids.info	
number of cores	1	
Frequency (MHz)	7.2	
Outer Dia. (mm)	12.7	toroids.info
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width/height (mm)	4.9	toroids.info
μ'	394.5	auto fill for
μ"	394.6	HF ham bands
Turns	3	
Cs (pFd)	0	
Al (nH)	222.10	
ΣA/l (m) flux crowding	0.0004480	
	real	imaginary
Y (S)	0.005529	-0.005528
Z (Ω)	90.5	90.4
|Z| (Ω)	127.9	
Ls (μH)	1.999	
winding length (cm)(inch)	10.6	4.2
winding length (cm)(inch)	12.8	5.0
expected effeciency	72.4%	
expected loss dB	1.405	

Compare With Online Calculator

Inputs:

Frequency (MHz)	7.20
OD (mm)	12.70
ID (mm)	7.150
Width (mm)	4.900
Chamfer (mm)	0
μ'	394.5
μ"	394.6
Turns	3.0
Cs (pF)	0.000

Calculate

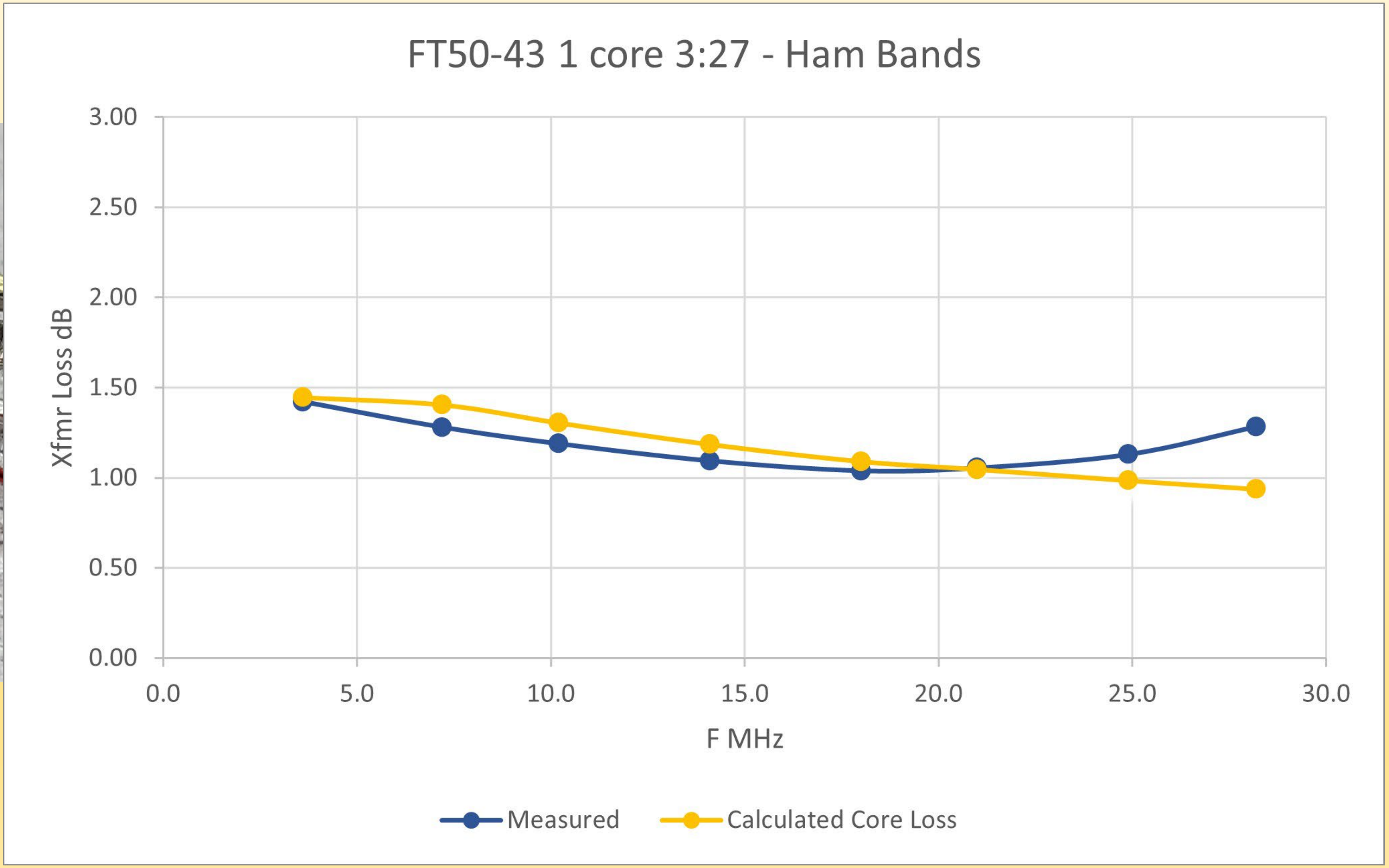
Results:

ΣA/l (m)	0.0004480
Y (S)	0.00553-j0.00553
Z (Ω)	90.5+j90.4
|Z| (Ω)	128
Ls (μH)	2.00

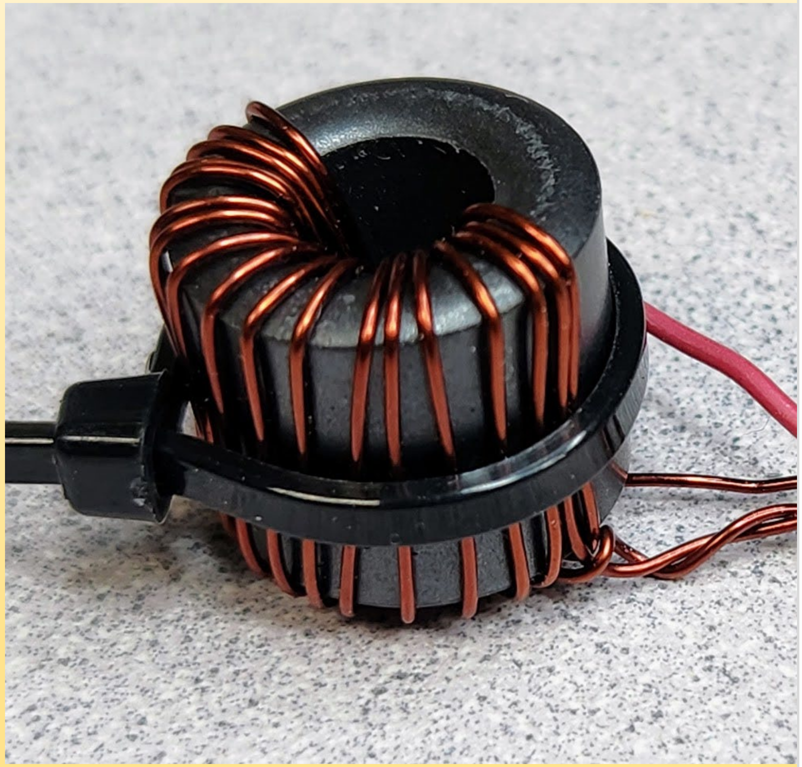
	Calculator for Fair-rite FT50-43 series	
	Physical dimensions from toroids.info	
number of cores	1	
Frequency (MHz)	7.2	
Outer Dia. (mm)	12.7	toroids.info
Inner Dia. (mm)	7.15	toroids.info
width/height (mm)	4.9	toroids.info
μ'	394.5	auto fill for
μ"	394.6	HF ham bands
Turns	3	
Cs (pFd)	0	
Al (nH)	222.10	
ΣA/l (m) flux crowding	0.0004480	
	real	imaginary
Y (S)	0.005529	-0.005528
Z (Ω)	90.5	90.4
|Z| (Ω)	127.9	
Ls (μH)	1.999	
winding length (cm)(inch)	10.6	4.2
winding length (cm)(inch)	12.8	5.0
expected effeciency	72.4%	
expected loss dB	1.405	

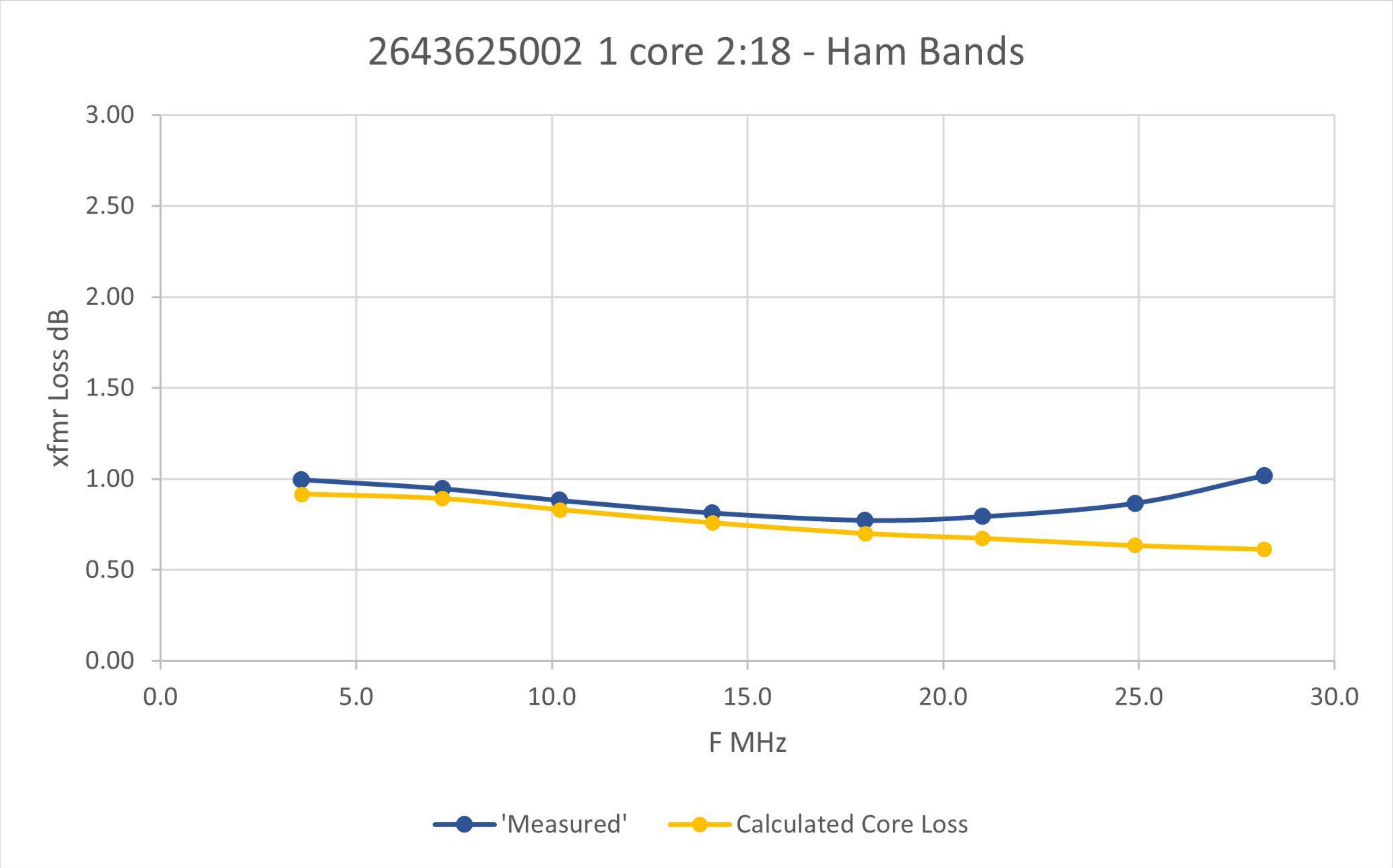
https://owenduffy.net/calc/toroid.htm Using Rectangular Cross-section Estimate

FT50-43 3:27 SOTA Transformer vs. Core Loss

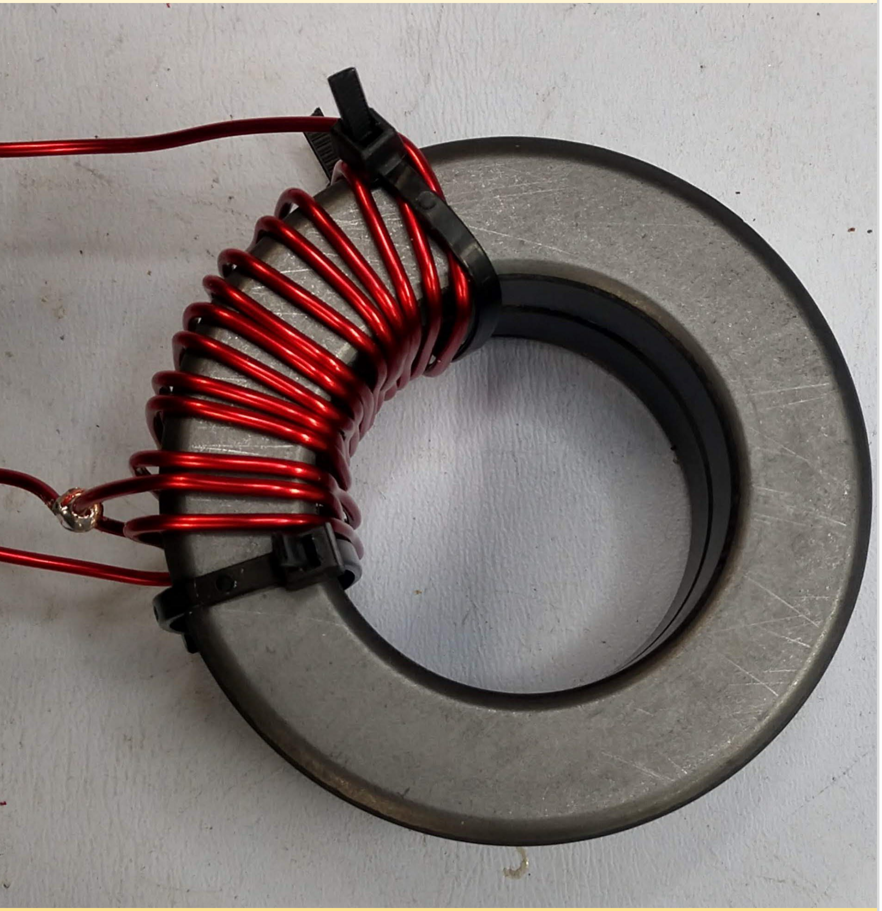


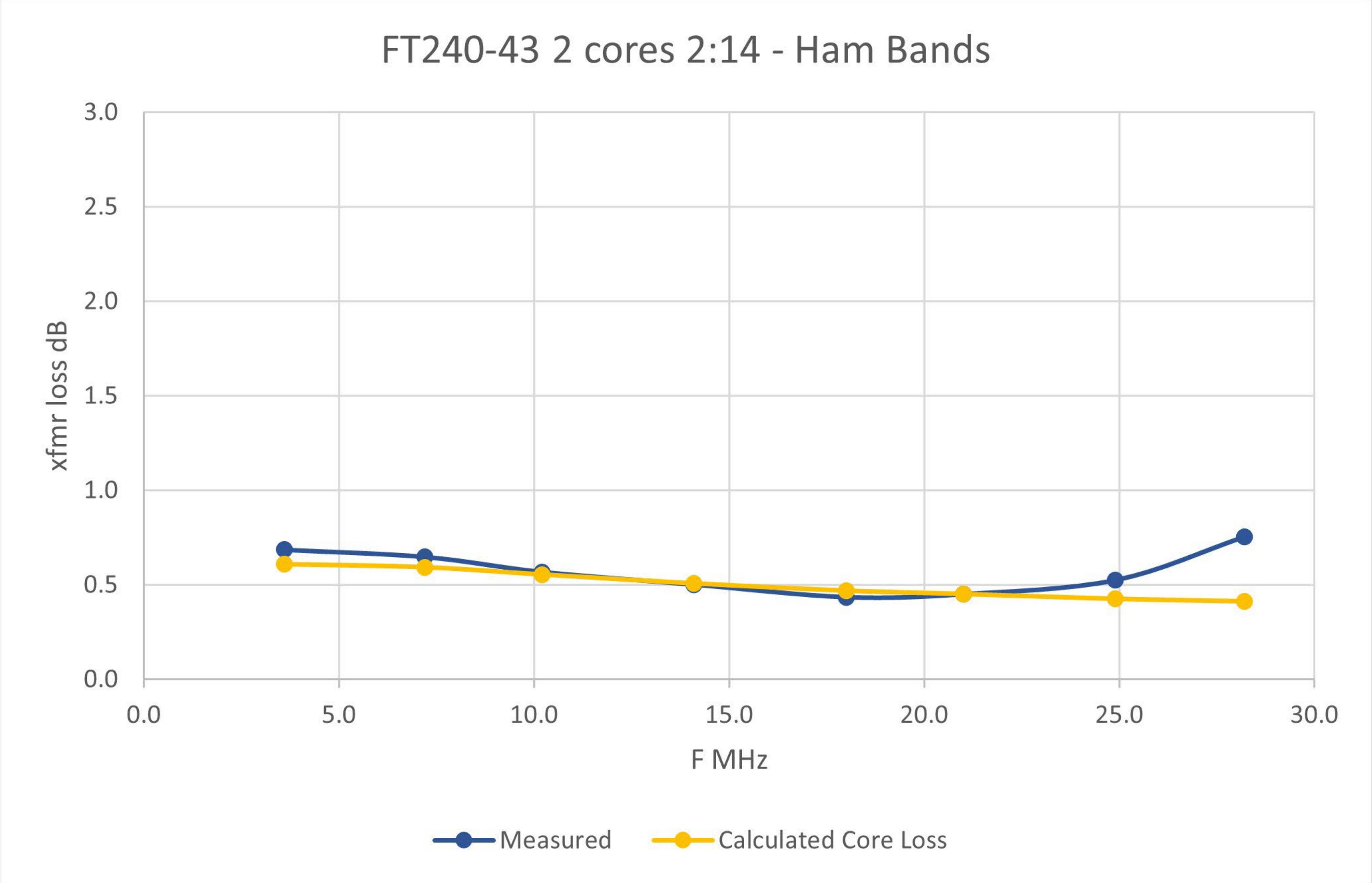
2643625002 2:18 SOTA Transformer





FT240-43 2:14 2 Cores QRO Transformer





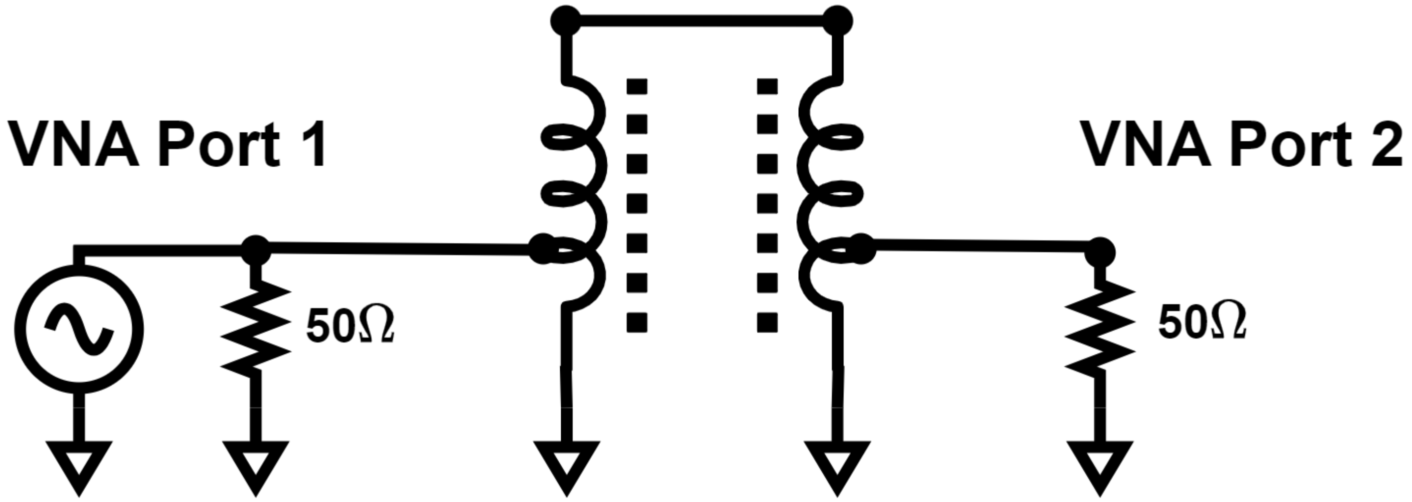
Measured vs. Core Loss

- Core Loss Dominant for Low HF Bands
- Other Losses at Higher Frequencies
  - Leakage Inductance
  - Winding Capacitance
- Core Loss Can be a Good Estimate of Transformer Loss for HF Bands

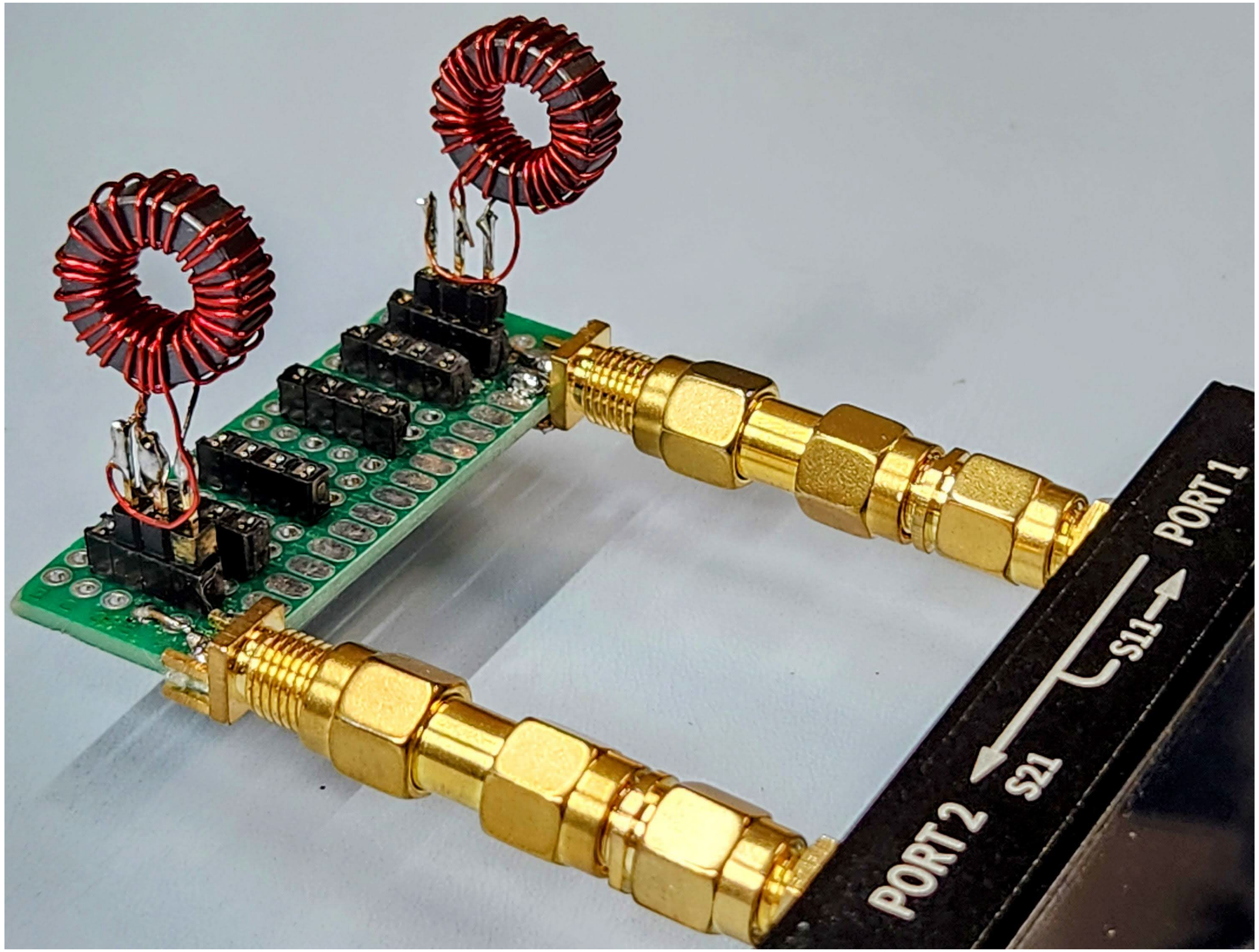
Measuring Transformer Loss

- Second Method
- Two Transformers
  - Back-to-Back
  - No Resistor Load
  - |S21| Insertion Loss
  - Wind Two Identical Transformers
- Often Used to Show Effect of Primary Capacitors

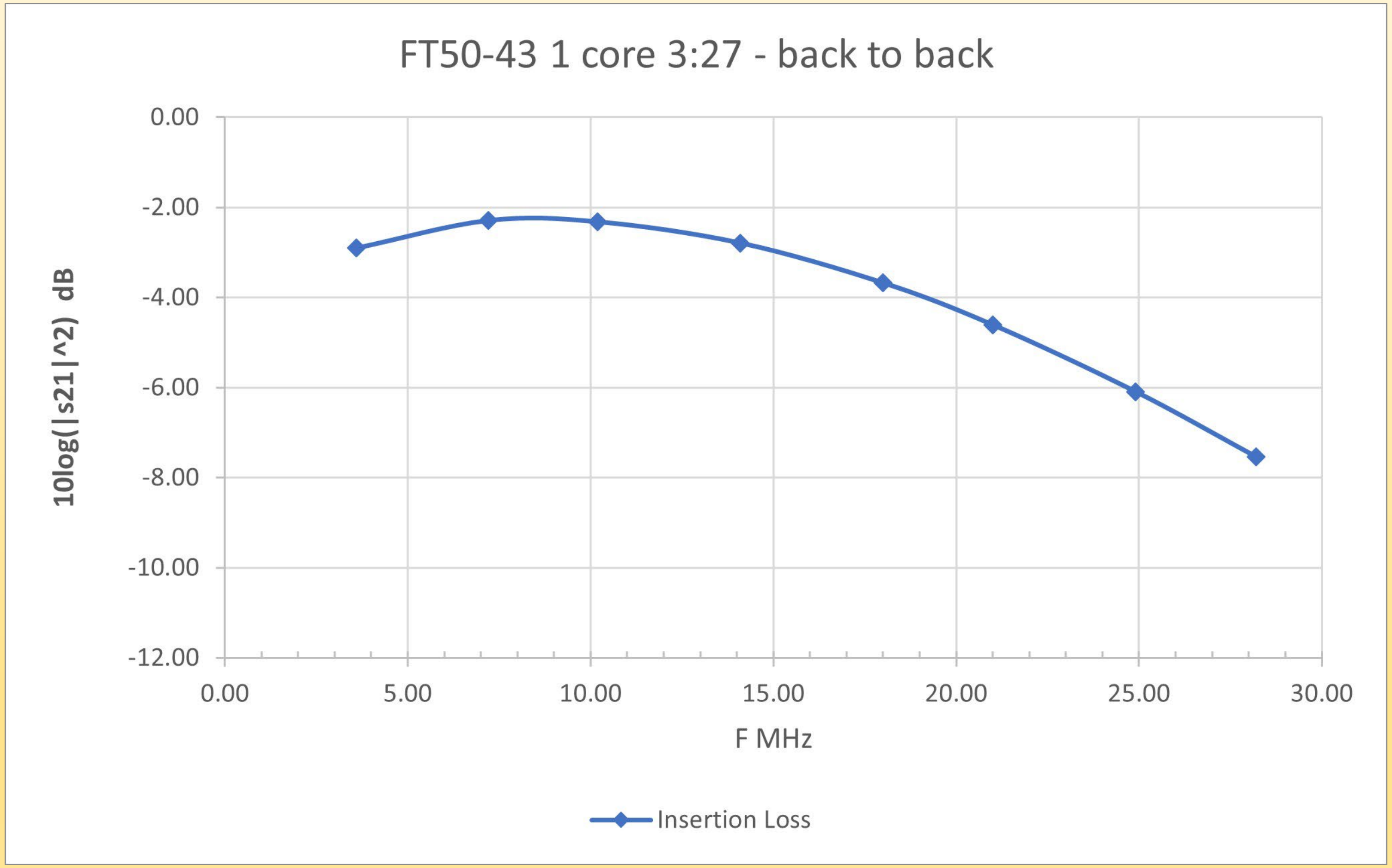
Back-to-Back Transformers



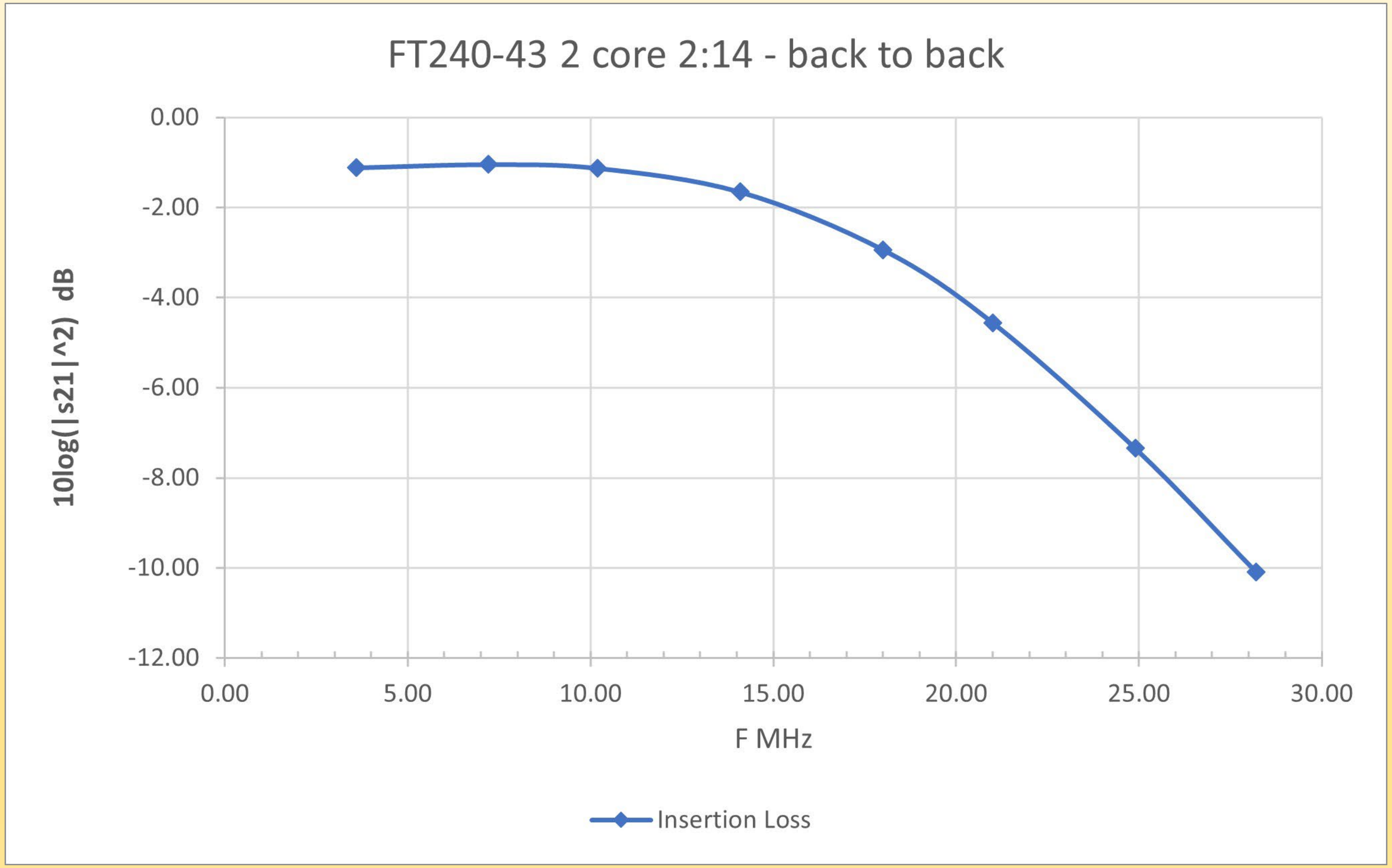
Back-to-Back Transformers



FT50-43 3:27 Back-to-Back



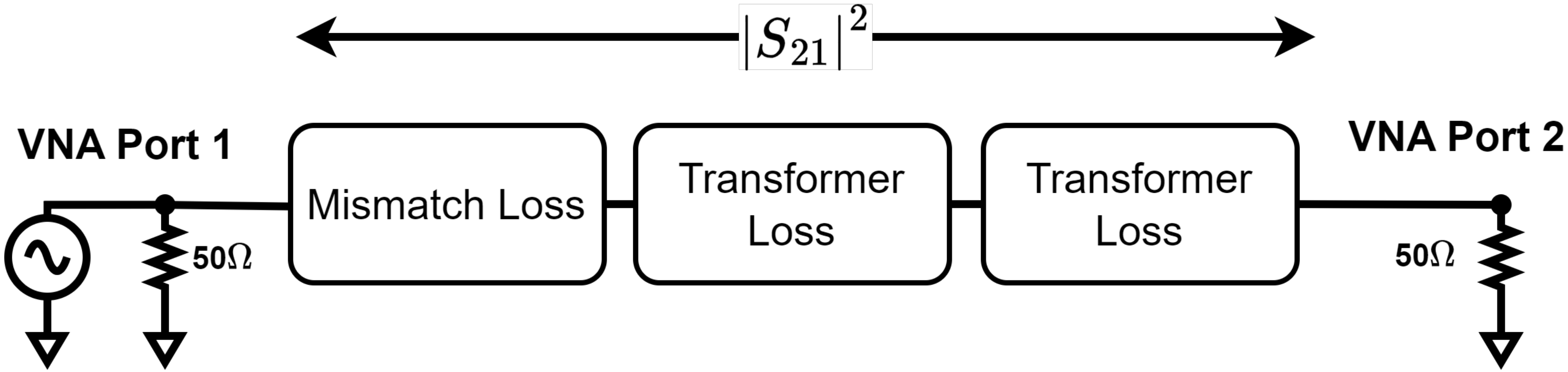
FT240-43 2 Cores 2:14 Back-to-Back



Transformer Loss Methods

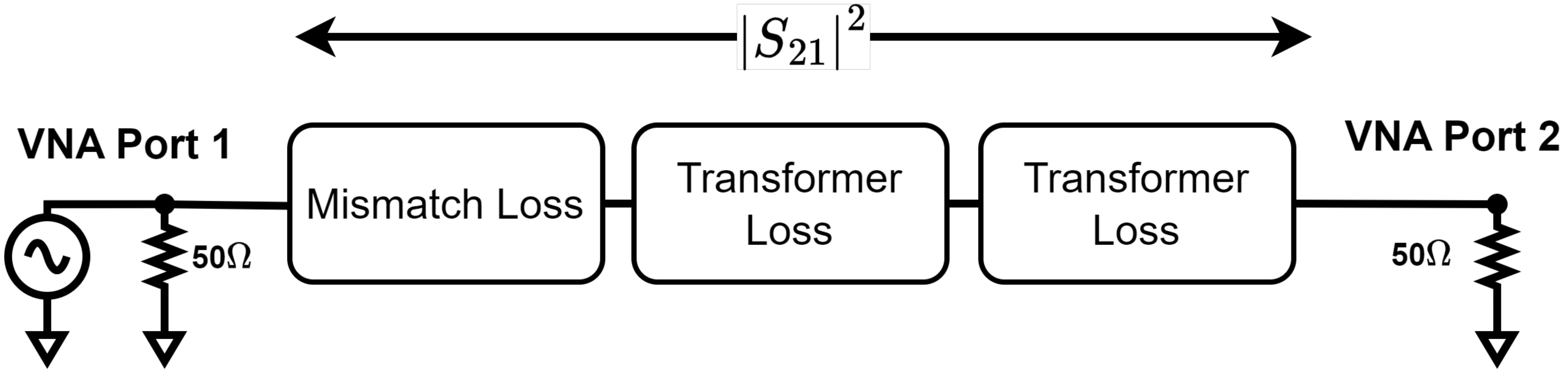
- Loss Appear to Be Different From First Method
- Are They Equivalent?
- Let's Look at the Details
  - Schematic

Back-to-Back Transformers



$$10\log\left(|S_{21}|^2\right) = MM_{loss}(dB) + 2 \times \text{xfmr}_{loss}(dB)$$

Back-to-Back Transformers



$$\mathrm{xfmr}_{loss}(dB) = \left(10\log\left(|S_{21}|^2\right) - MM_{loss}(dB)\right)/2$$

Transformer Loss Equivalent Between Methods?

- Next Set of Measurements
  - Wind Two Identical Transformers
  - Characterize Each Individual Transformer
    - Single Transformer with Load - First Method
    - Transformer Loss

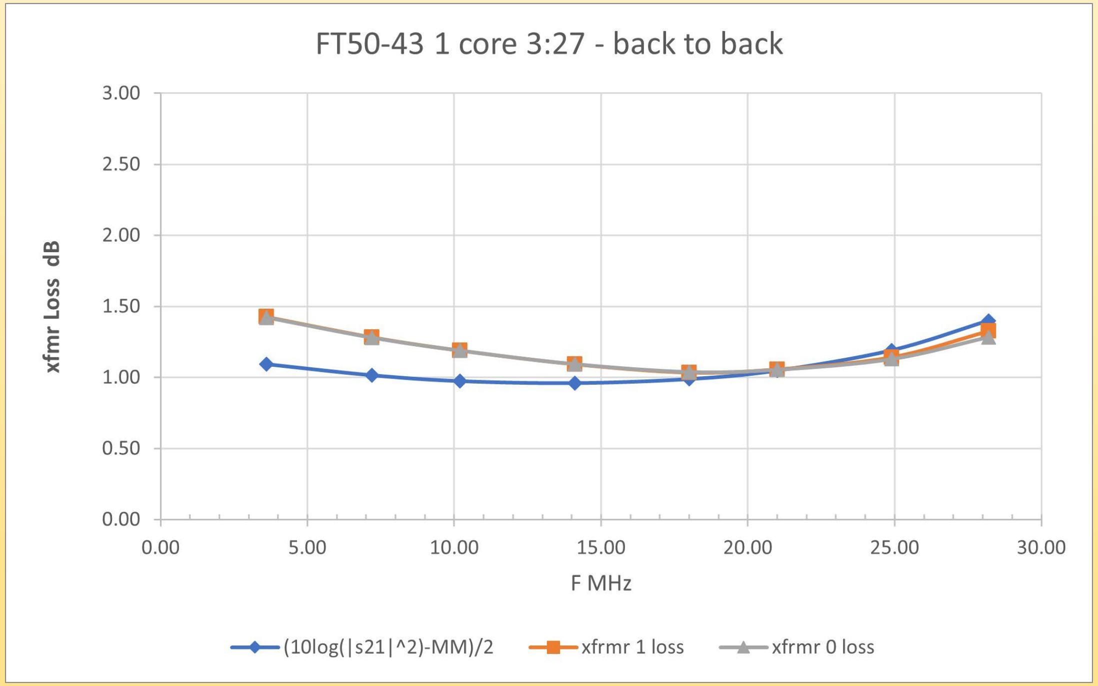
Transformer Loss Equivalent Between Methods?

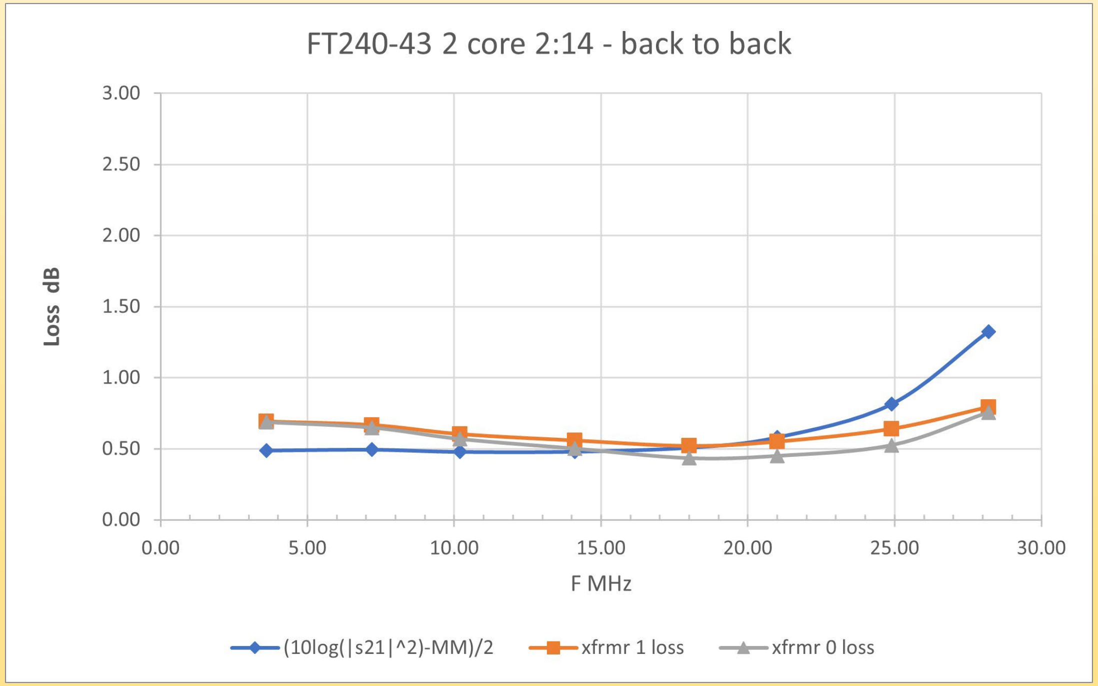
- Characterize the Transformer Pair
  - Back-to-Back – Second Method
  - Insertion Loss
  - Mismatch Loss

Transformer Loss Equivalent Between Methods?

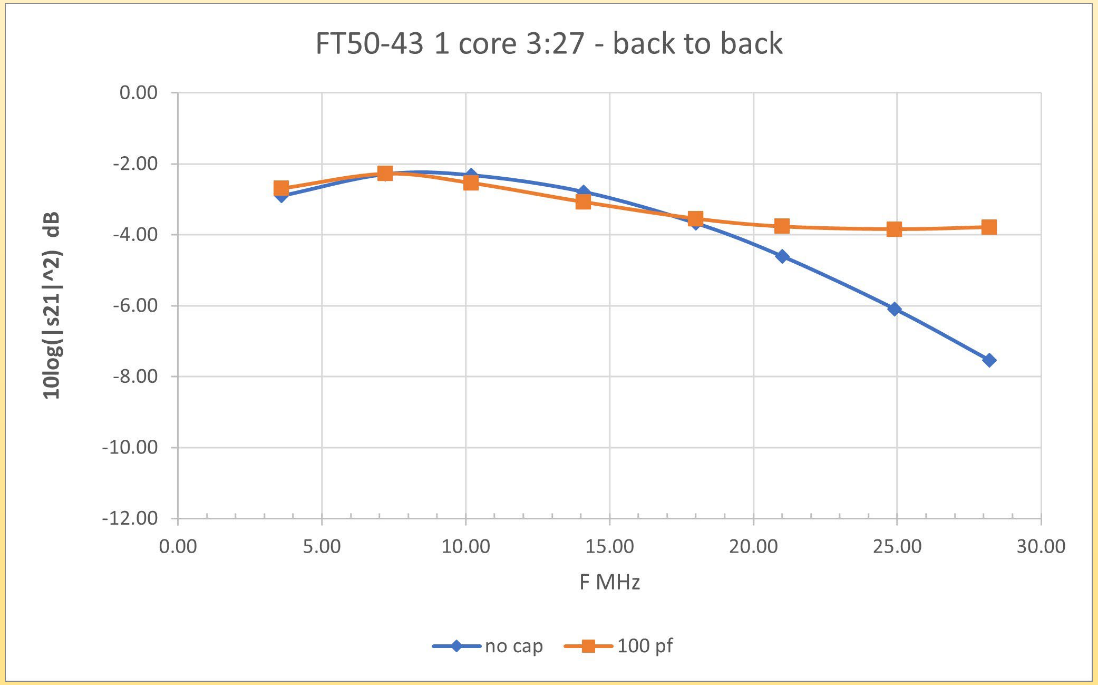
- Plot Each Set of Measurements
  - Transformer Loss From First Method
  - Insertion and Mismatch Difference
    - From Back-to-Back
  - $\left(10\log\left(|S_{21}|^2\right) - MM_{loss}(dB)\right)/2$

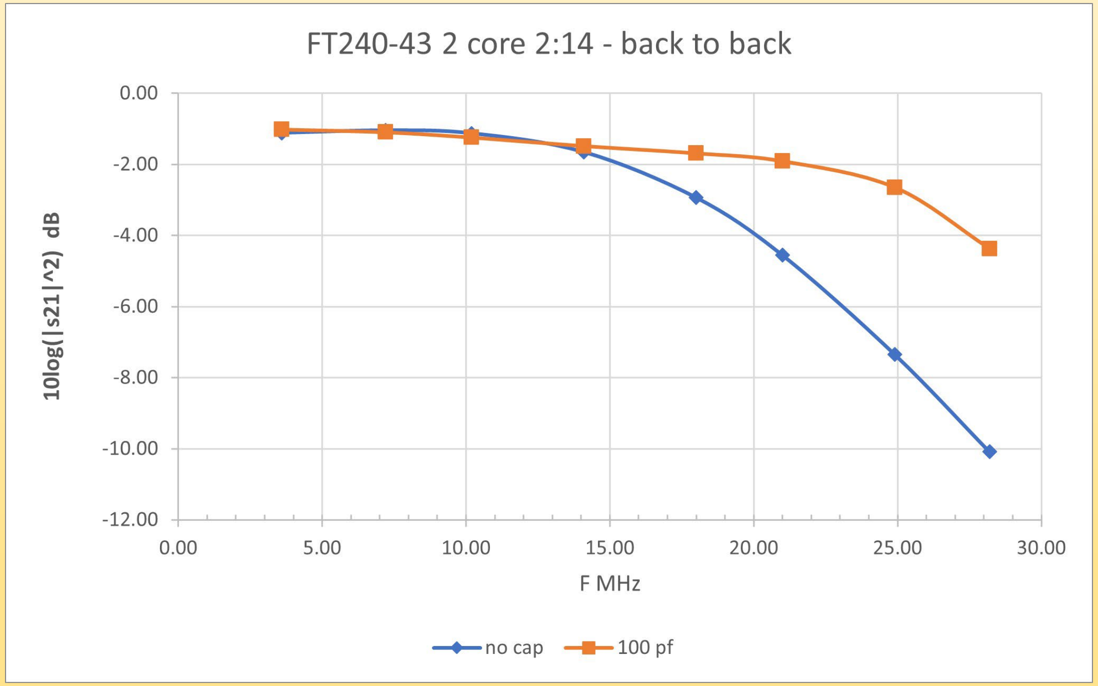
Back-to-Back vs. Single Transformer



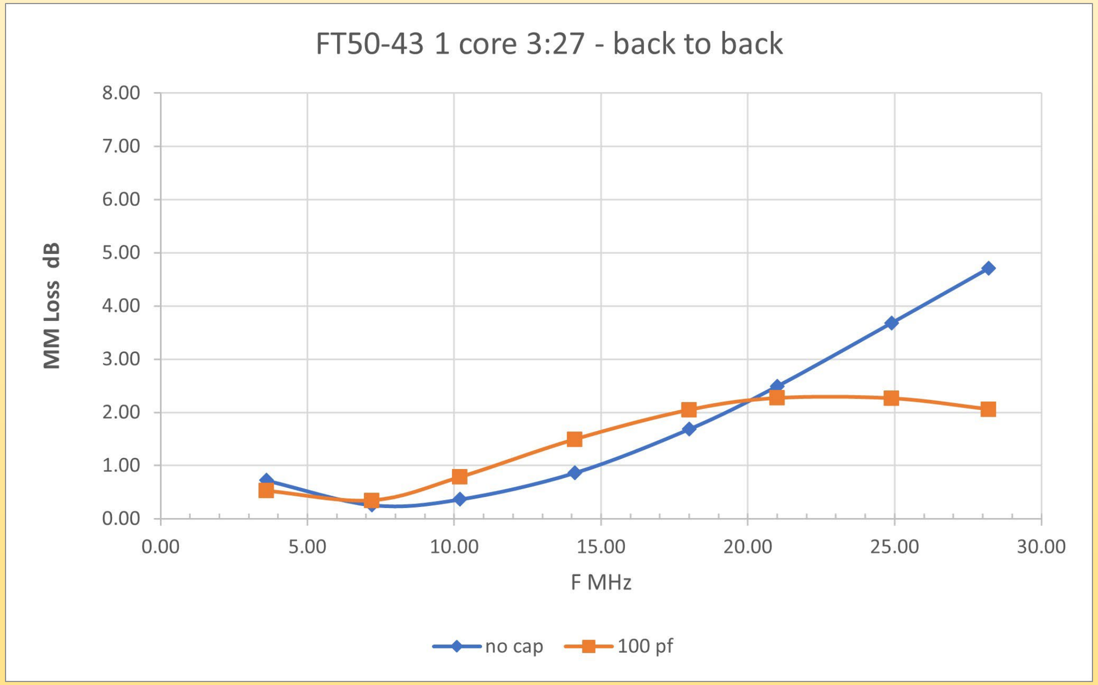


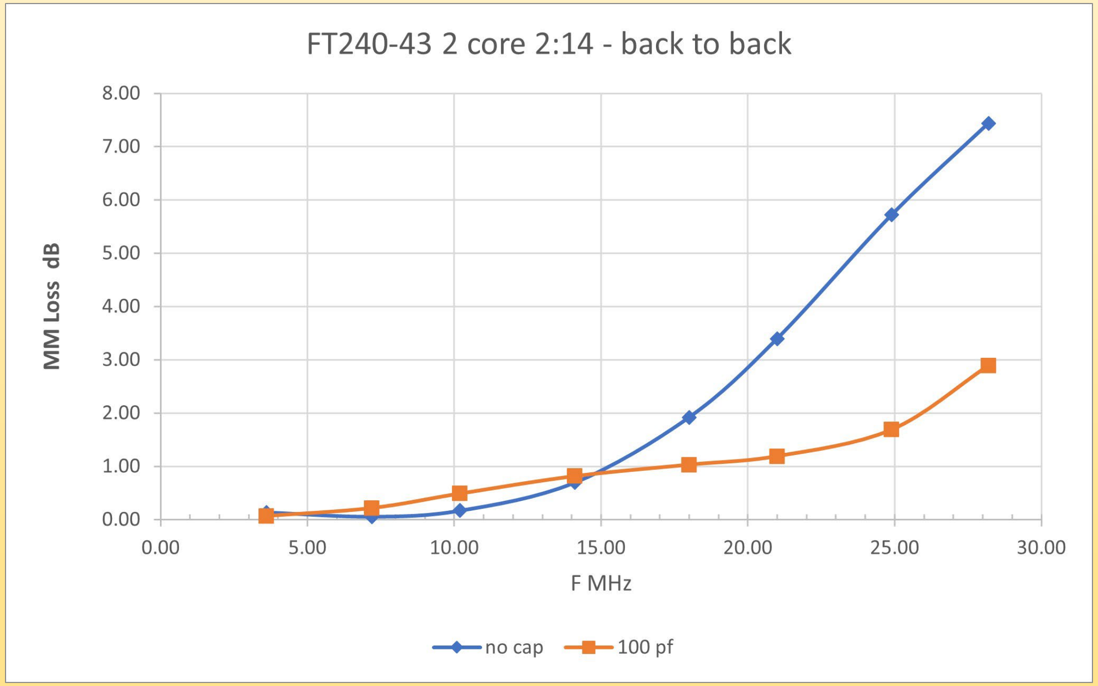
Primary Capacitor Reduces Insertion Loss



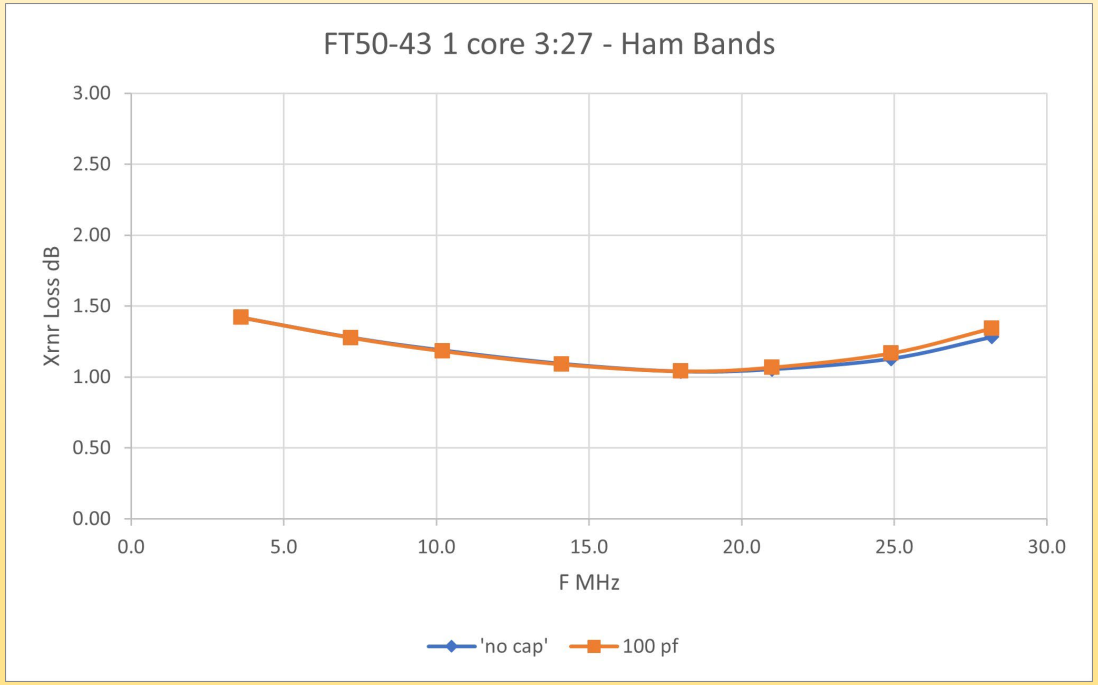


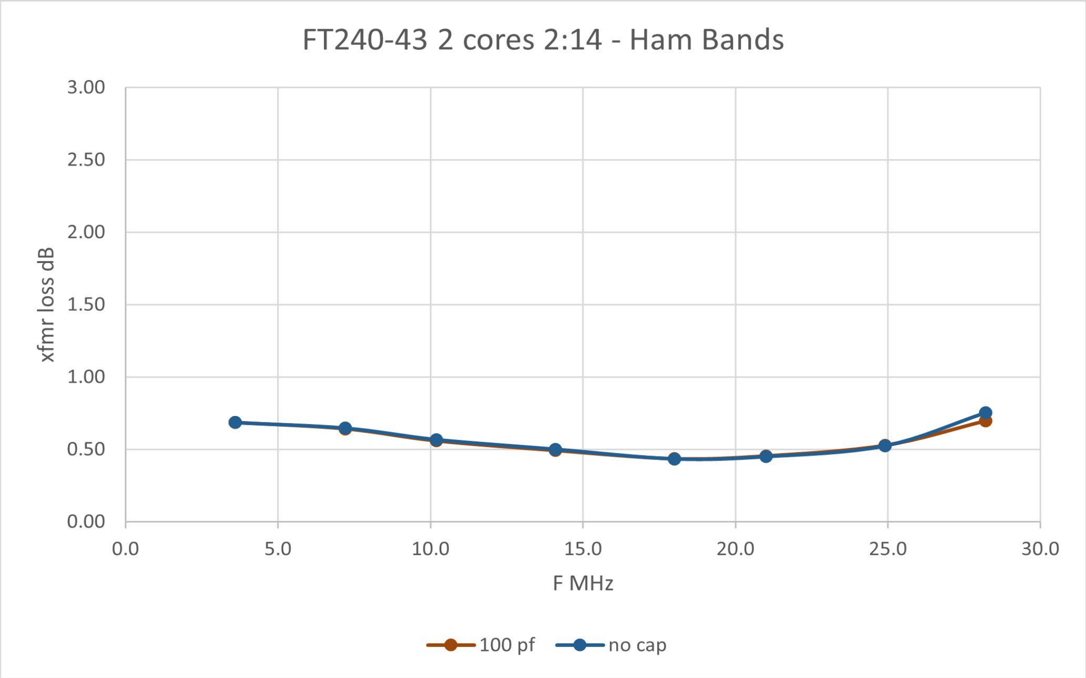
Primary Capacitor Reduces Mismatch Loss





Primary Capacitor Has Essentially No Affect on Transformer Loss





Back-to-Back Transformers

- Method Equivalence
  - General Agreement Between Methods
  - Mismatch Included in Back-to-Back
- Primary Capacitor
  - Reduces Mismatch Loss
  - Does Not Affect Core Loss

Method Comparison

Transformer plus Load

- Single Transformer
- Well Characterized Load Resistor
- Transformer and Mismatch Loss as Separate Data
- Calculations Required

Back-to-Back

- Two Transformers
- No Load Resistor
- Mismatch Loss Part of Result
- Few Calculations Needed

Measurement Considerations

- Test System Calibration
  - nanoVNA at Operating Temperature
  - Calibrate nanoVNA Attached to Test Fixture
    - Across Test Frequency Range
    - Short and Load on Header
    - 50Ω Load is SMD Like Load Resistor

Measurement Considerations

- Load Resistor
  - Measure Complex Impedance Across Test Frequency Range
  - In Test Fixture Position
  - SMD Mounted on Header

Measurement Considerations

- Transformer Loss is Sensitive to Measurement
  - Small Number That is a Difference of Two Much Larger Numbers (Insertion Loss and Load Loss)

$$\mathrm{xfmr}_{loss}(dB) = 10\log\left(|S_{21}|^2\right) - MM_{loss}(dB) - Load_{loss}(dB)$$

  - Small Deviation in Measurement Values has a Large Effect on Transformer Loss

Small Deviation Produces Nonsensical Data

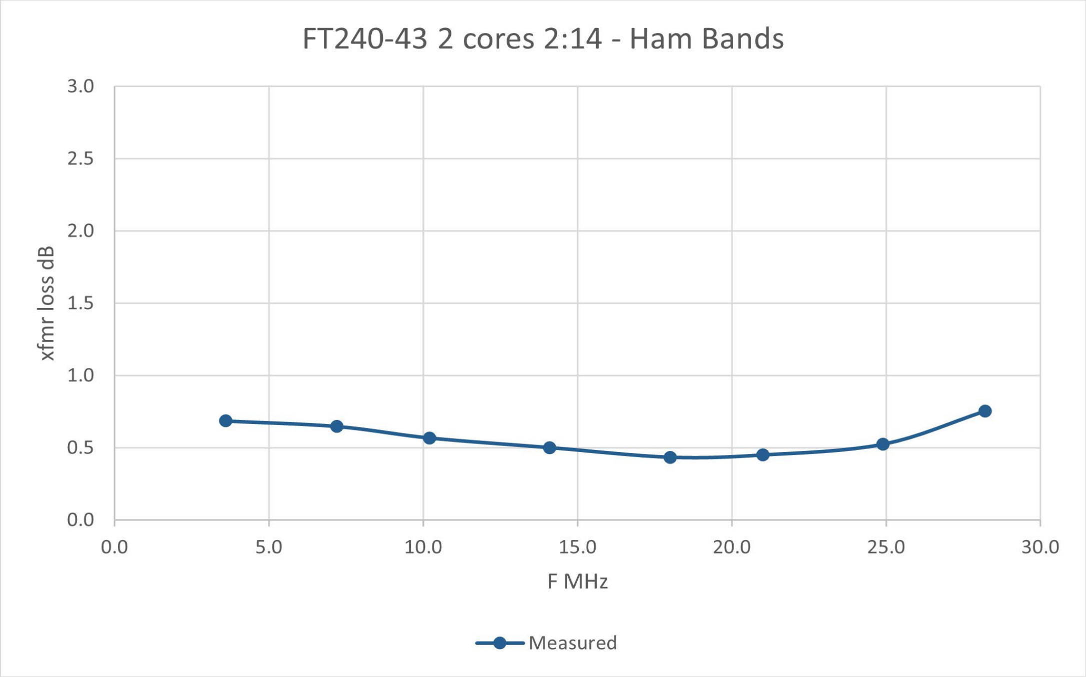
- Very Low Loss Transformers Difficult to Measure
- Test Procedure Important
- Limited by VNA Capabilities

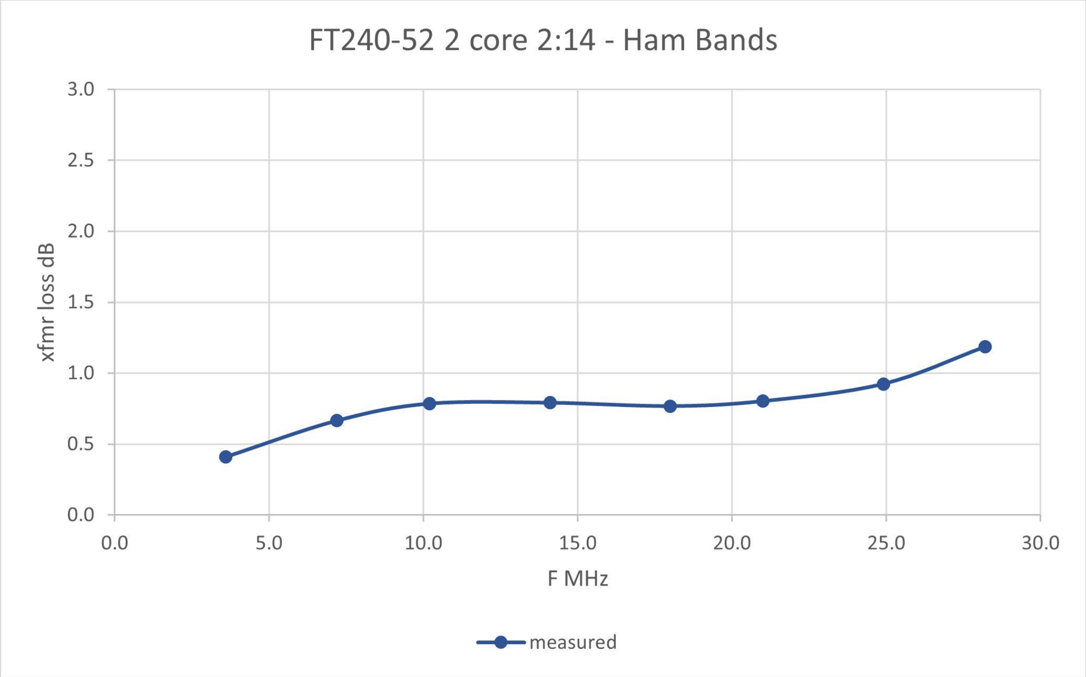
Measured Values FT240-43 x2 2:14				
Freq (MHz)	10log(|s21|^2) (dB)	Load_loss (dB)	xfmr_loss (dB)	xfmr_eff (%)
3.60	17.06	16.34	0.69	85.3
7.20	17.10	16.32	0.67	85.8
10.20	17.22	16.29	0.60	87.0
14.10	17.58	16.21	0.56	87.9
18.00	18.25	16.13	0.52	88.7
21.00	18.97	16.03	0.55	88.1
24.90	20.15	15.92	0.64	86.3
28.20	21.31	15.80	0.79	83.3

Δ1% S11 S22 ZLoad	
xfmr_loss (dB)	xfmr_eff %
-0.15	103.5
-0.17	104.0
-0.23	105.5
-1.12	129.5
-1.15	130.5
-1.13	129.6
-1.03	126.8
-0.88	122.4

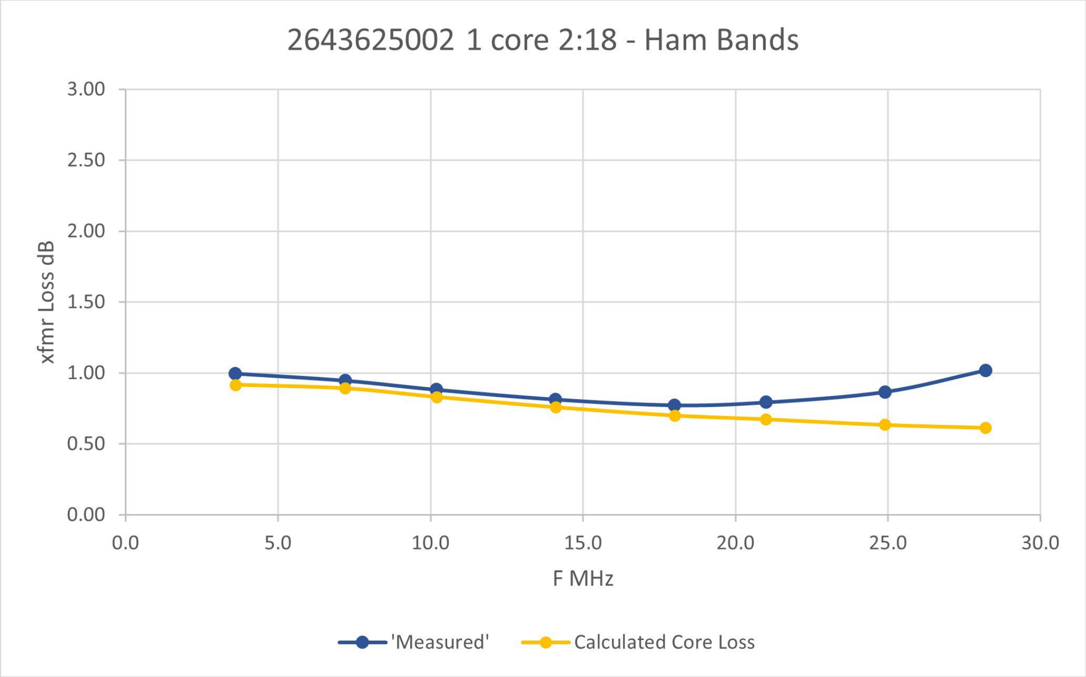
Transformer Loss Measurement Examples

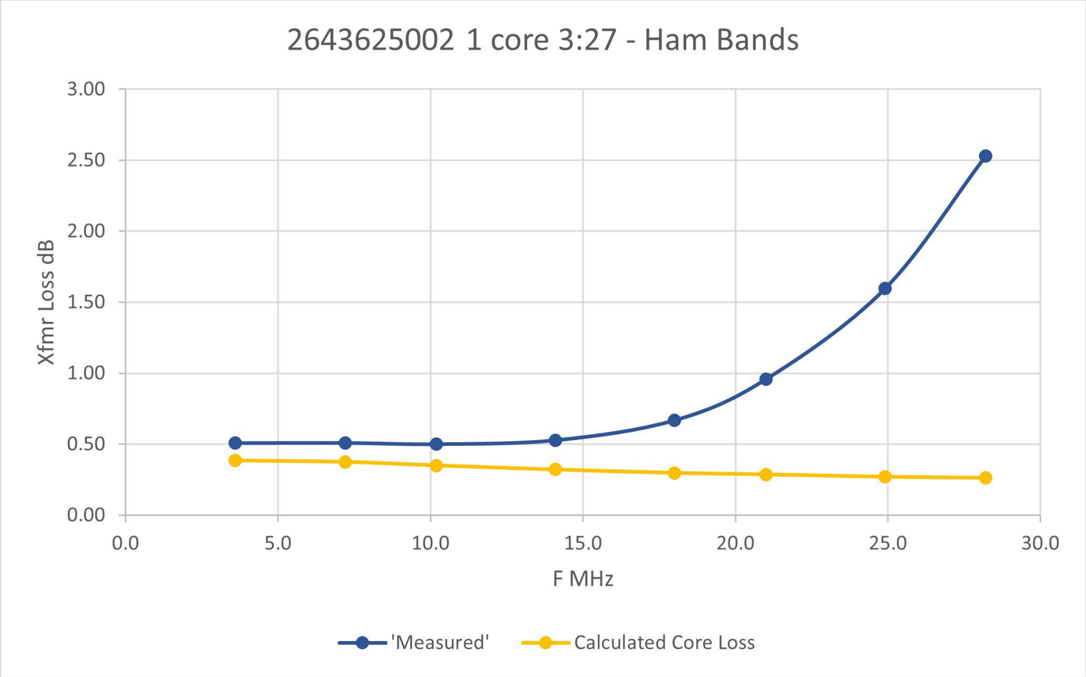
Transformer Loss: Comparing Material Type



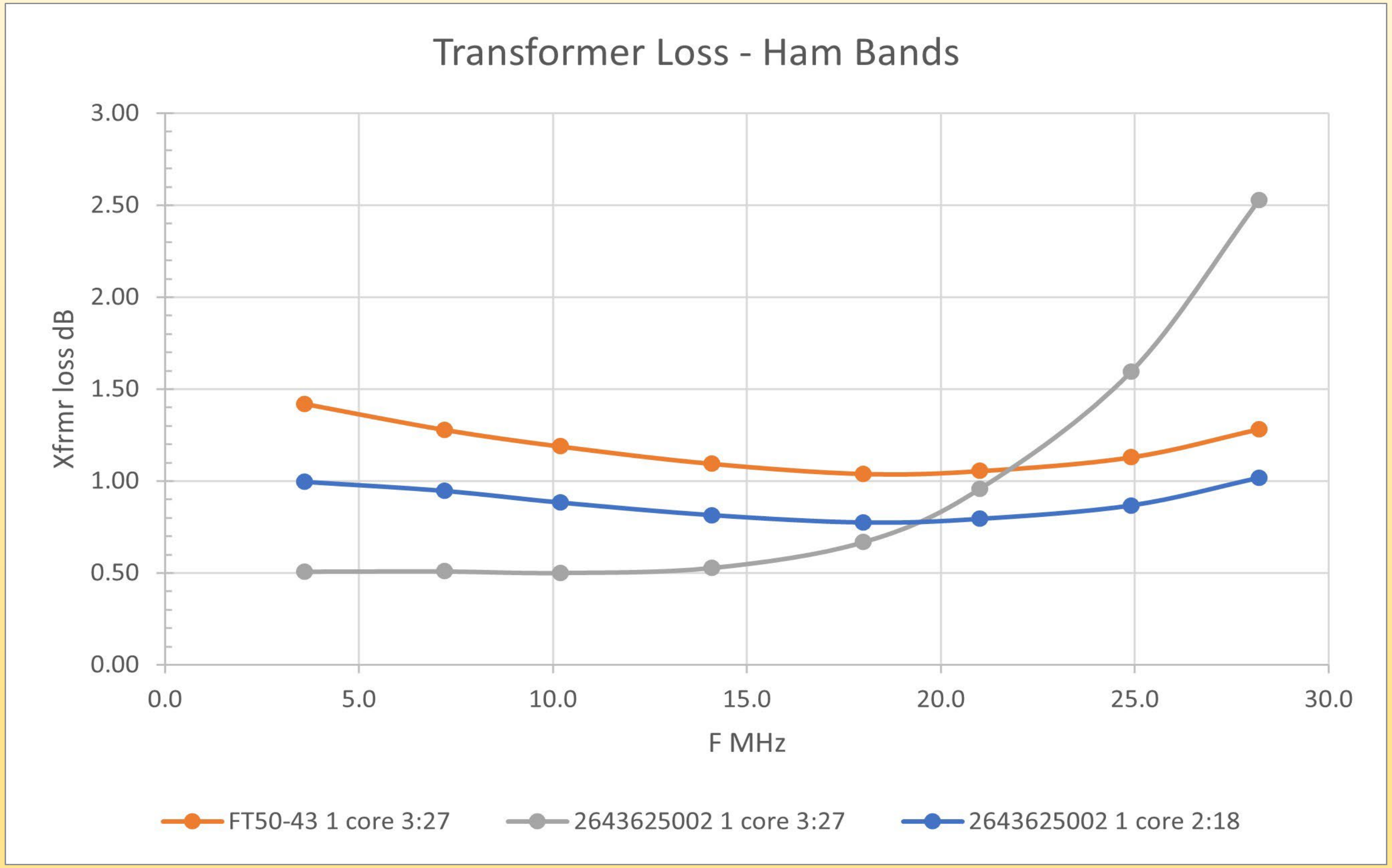


Transformer Loss: Comparing # of Turns





Transformer Loss: Comparing # of Turns



How Turns Affect Transformers

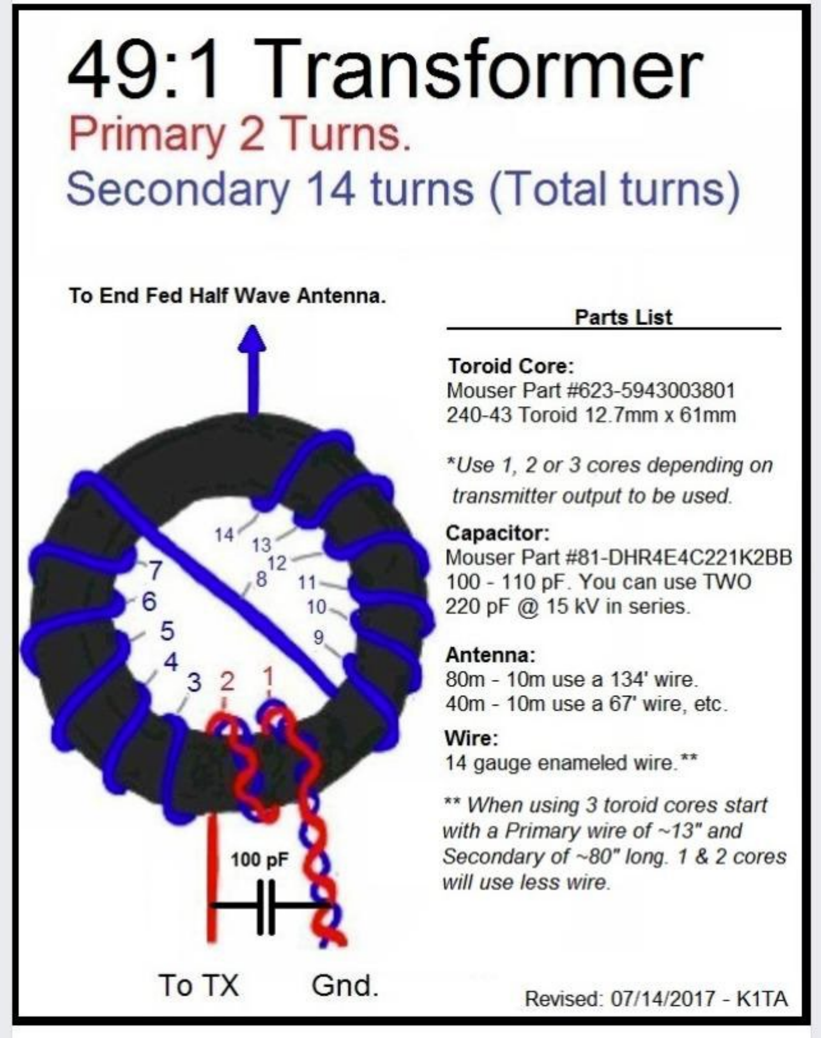
- More Turns Reduce Core Loss

$$\text{eff} = 1 - G_{cl}/G_s \qquad R = 2\pi f N^2 A_l \left(\frac{\mu''}{\mu_i} \right)$$

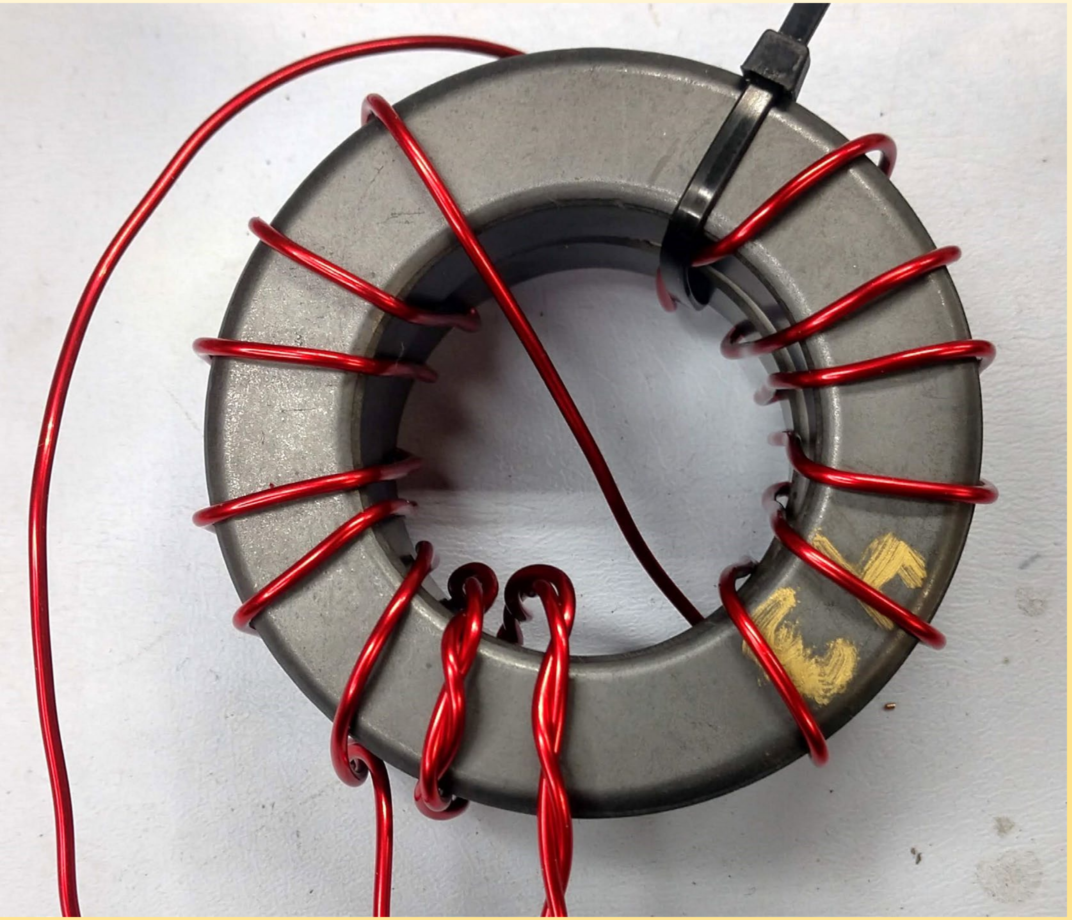
- More Turns Increase High HF Band Transformer Loss
  - Winding Capacitance
  - Leakage Inductance
- Wide Bandwidth Transformers
  - Balance Higher Core Loss at Low HF for Lower Transformer Loss at High HF

Transformer Loss: Comparing Winding Style

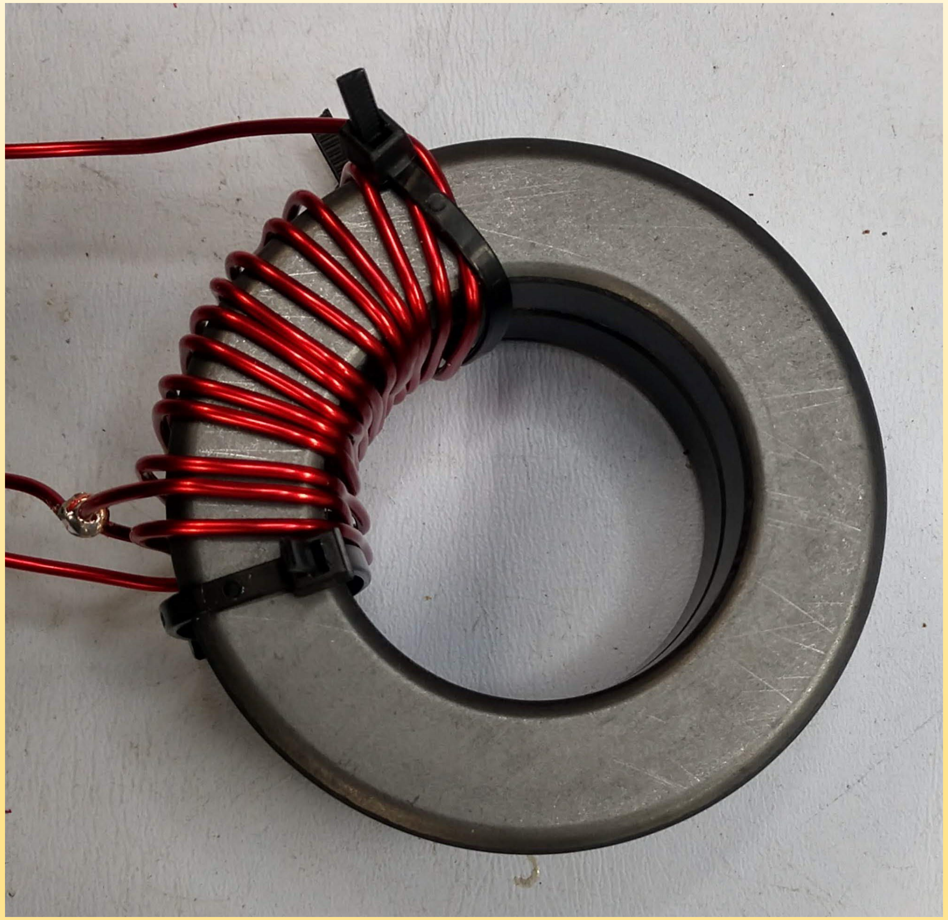
- Conventional Wisdom
  - Primary is Twisted Over Secondary
  - Secondary Crossover after Seven Turns
  - Why?
- Should I Use This For My QRO Base Station?



Transformer Loss: Comparing Winding Style

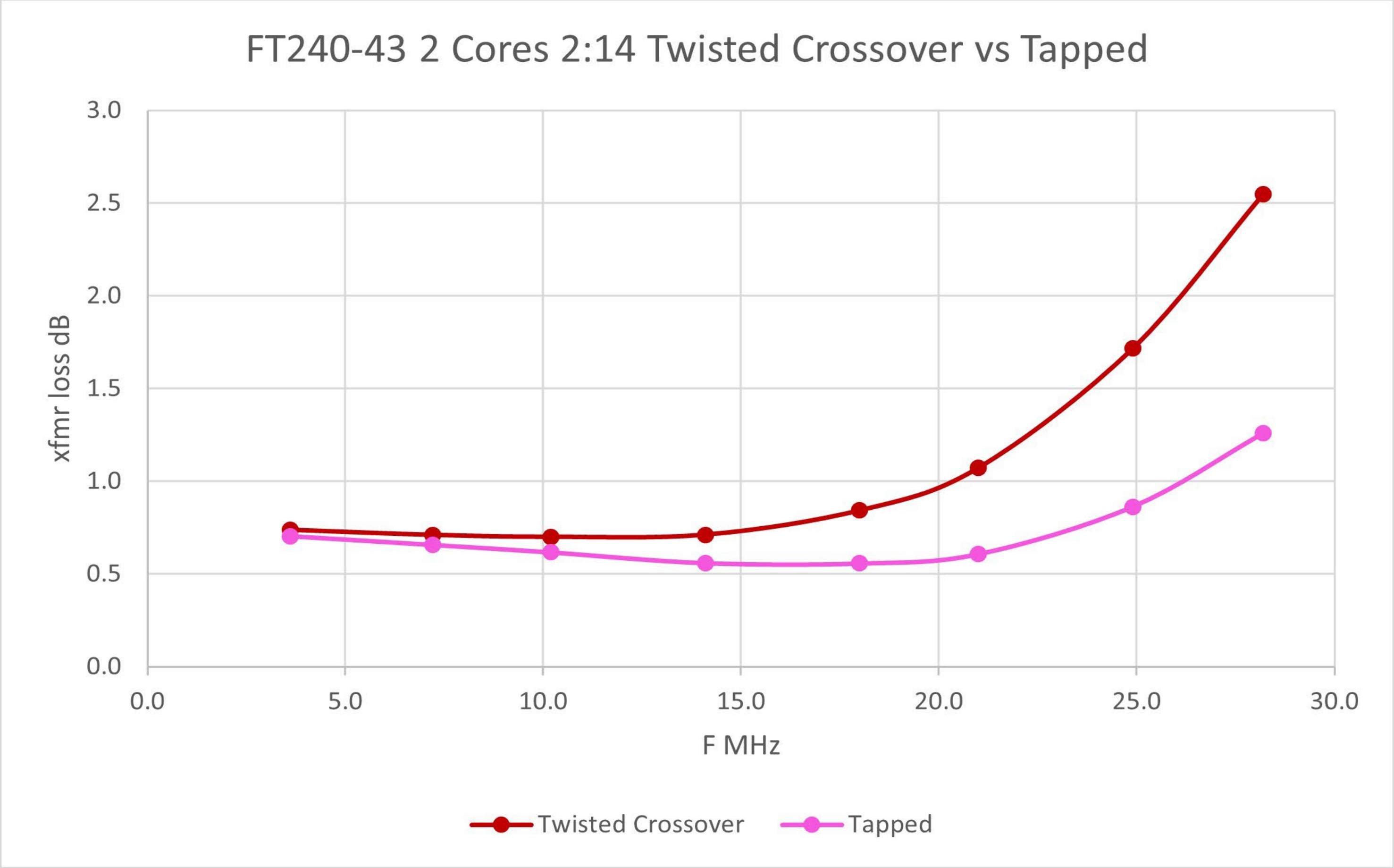


Twisted Primary with Crossover

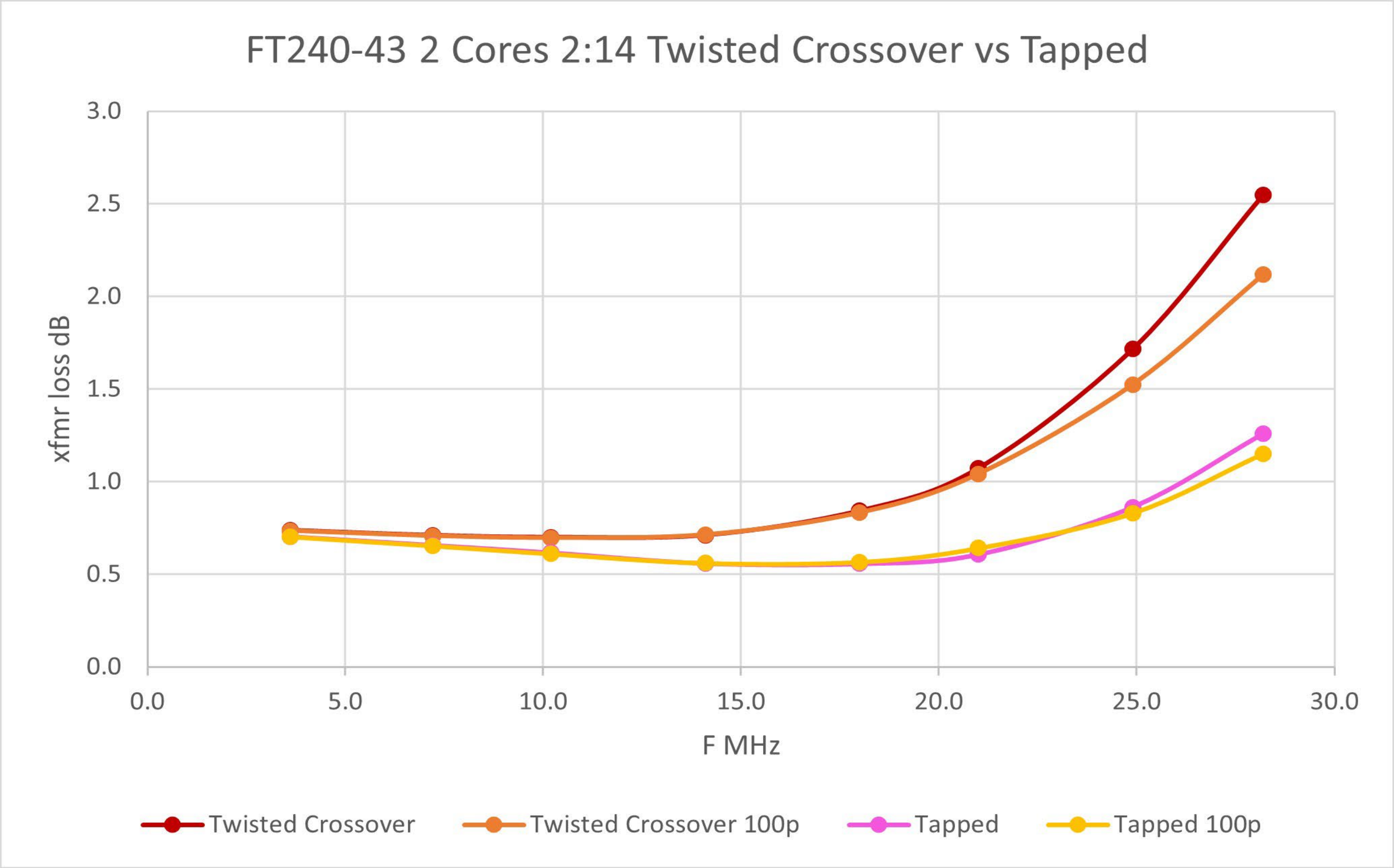


Tapped Single Winding

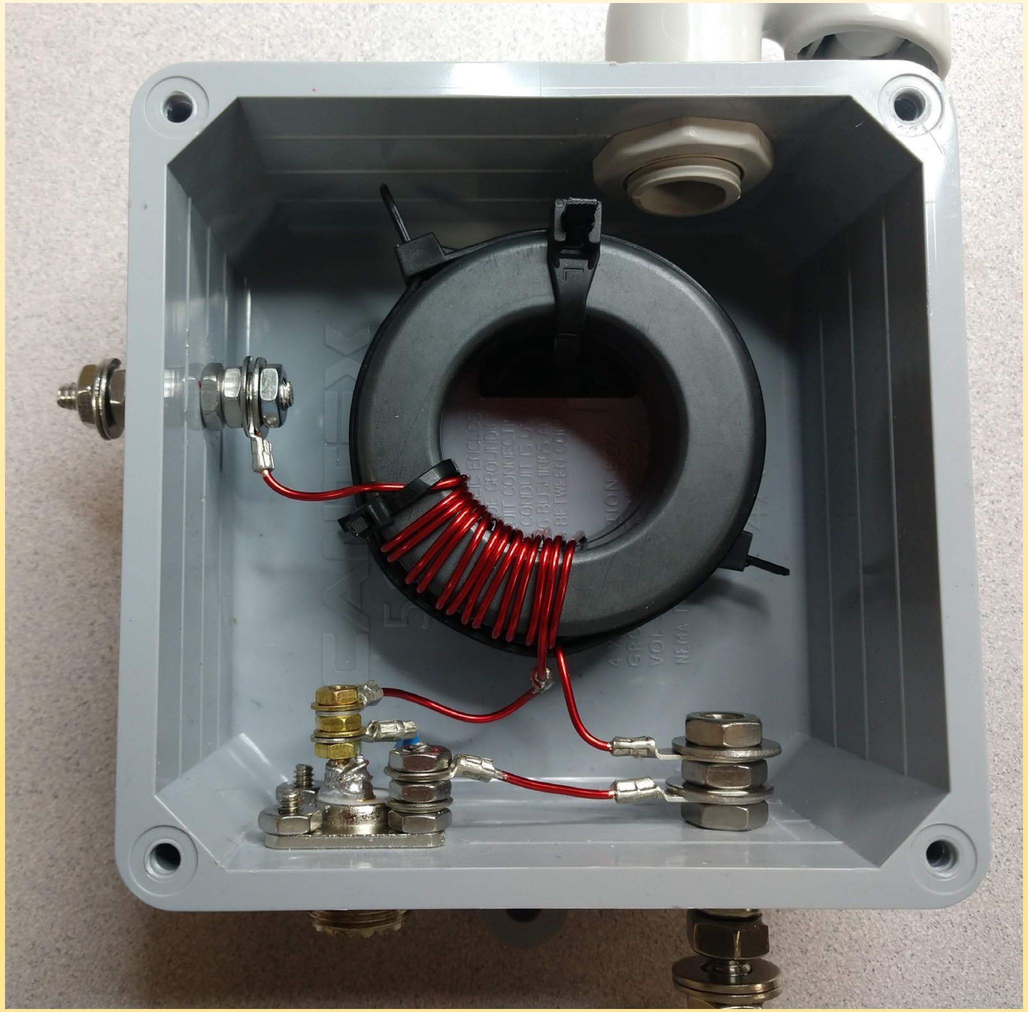
Transformer Loss: Comparing Winding Style



Transformer Loss: Comparing Winding Style



Transformer Loss: Comparing Winding Style



What We Learned

- Ferrite Core Characteristics Vary With Frequency
- Ferrite Cores Have Real Resistance – Core Loss
  - Power Loss and Heat
- Two Methods to Measure Transformer Loss
- Core Loss Can be a Good Estimate for HF Transformer Loss
- Transformer Loss is Sensitive to Measurement
- Transformer Loss Measurement is Fun -> Try It!

References

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- https://github.com/phase2682/FC-XFMRS-AI6XG
- A method for estimating the impedance of a ferrite cored toroidal inductor at RF – Owen Duffy
- https://owenduffy.net/calc/toroid.htm
- https://owenduffy.net/calc/toroid2.htm